A STRUCTURAL STUDY OF THE SEPARATION POINT BATHOLITH: EMPLACEMENT MECHANISMS AND THE TECTONIC REGIME.

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THESIS

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ABSTRACT

The Separation Point Batholith is a late Cretaceous granitic intrusion outcropping in the north-west Nelson region of New Zealand. The batholith is elongate, oriented north / south, and stitches the Paleozoic Takaka Terrane to the arc-derived Median Tectonic Zone. It has been found to be related geochemically to high-Al trondhjemite-tonalite-dacite suites, and hence to be related to the Western Fiordland Orthogneiss.

This study investigates the structural features of the northern segment of the Separation Point Batholith where they are exposed along the coastline of the Abel Tasman National Park. Extensive measurements of the pervasive foliation and lineation indicate a consistent planar structure dipping moderately to steeply to the east, and a linear structure plunging gently to the north-east. Jointing systems are approximately consistent with this structure. The western margin is marked by a zone of intense strain, also producing structures dipping steeply to the east, and by the mixing of granitic and dioritic magmas.

A model for the emplacement of the Separation Point Batholith has been developed based upon tectonic reconstructions for magma genesis and later post-compressional events. The batholith was emplaced in an active tectonic environment under a transpressional regime, along a major north-south striking oblique shear zone with dextral strike-slip and east-over-west thrusting. Dilational jogs along the shear zone provided the room for intrusion, and the batholith was finally emplaced into releasing bends of high-level fault systems.

CHAPTER 1

INTRODUCTION

1.1: AIMS

The aim of this thesis is to investigate the structure of the Separation Point Batholith in an attempt to gain more information on the tectonic regime at the time of its emplacement. The area was chosen for several reasons: coastal outcrop is excellent, allowing for a detailed structural study; the study would support, and be supported by, the recent geochemical studies carried out on the granite; and the granite was emplaced at an important time in the history of New Zealand geology, further structural information for this time period therefore being especially important.

The primary aim of this thesis, therefore, is to obtain a collection of structural data from as extensive an area of the batholith as possible. In particular, the attitude of any foliation or lineation would be especially useful, as would any indication of shear sense associated with these structures. Jointing patterns and orientation of dikes and shear zones may also provide additional information to assist in determining the structure of the batholith.

Analysis of data from such a wide area should allow for the recognition of regional patterns without being significantly distorted by local variation. On the other hand, areas where significant variation from regional patterns occurs should also be made apparent. From these data, it is hoped that some indication of the stress state at the time of intrusion can be determined, along with a history of the deformational events associated with emplacement.

The results of such analysis would be useful to develop or constrain tectonic models set around the time of the emplacement of the batholith. In particular, any information on the state of stress or its regional variability at this time would be useful in determining the tectonic regime, as would the attitude and sense of any localised intensive strain.

This study will also look at the occurrence and nature of small scale structural features. Pegmatites, in particular, will be examined, and their occurrence and internal structure documented, as will enclaves, and local areas of magmatic heterogeneity.

1.2: AREA

This study was carried out along the coastline of the Abel Tasman National Park, located in the North West Nelson region of the South Island of New Zealand (Fig 1). This coastline is dominated by the granitic rocks of the Separation Point Batholith, with minor occurrences of younger cover sediments. The granite is exposed from the western end of Tata Beach, just beyond the North West boundary of the national park, to Anawera Point south of Kaiteriteri Beach (Map 1).

Accessibility to the coastline is good at either end of the area, with roads following the coast and giving access to the beaches, but within the Abel Tasman National Park road access is only available in to Totaranui

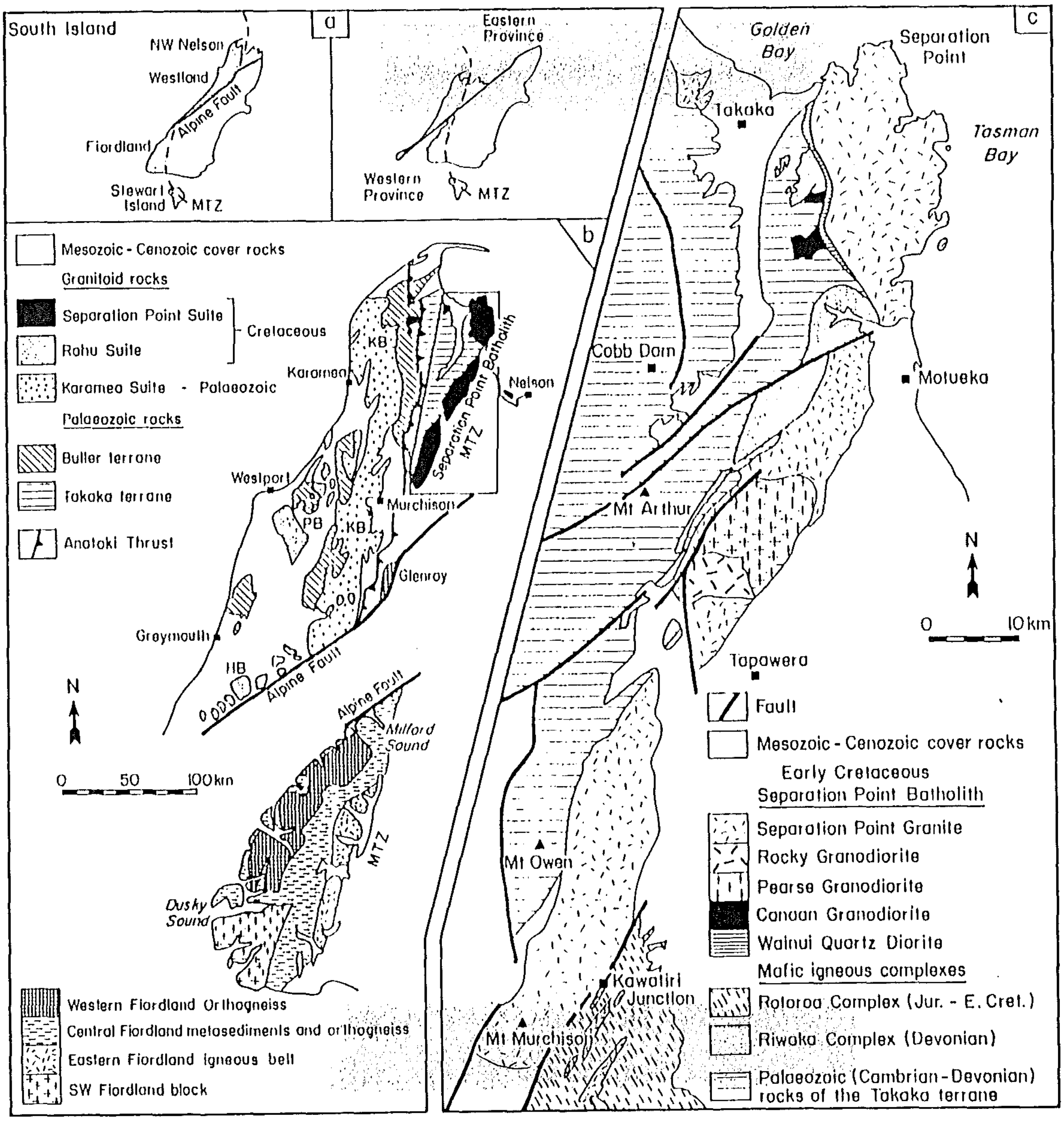


Figure 1a: Configuration of the South Island, New Zealand before and after movement of the Alpine Fault (after Landis & Coombs, 1967; Muir et al, 1995a). MTZ = Median Tectonic Zone (J. D. Bradshaw, 1993).
Figure 1b: Geological map of NW Nelson-Westland and Fiordland showing the distribution of the Separation Point Batholith (after Tulloch, 1988; Cooper, 1989; J. Y. Bradshaw, 1990; Muir et al, 1995a). KB = Karamea Batholith, PB = Paparoa Batholith, HB = Hohonu Batholith.
Figure 1c: Geological map of the Separation Point Batholith (after Grindley, 1971; Grindley, 1980; Coleman, 1981; Suggate, 1984; Muir et al, 1995a).

Beach. Further access is only available by boat or along the extensive and well-maintained Coastal Track (Map 1). Outcrop occurs along the rocky shoreline between beaches, and is best exposed in wave-cut shore platforms and sea cliffs. Above the cliffs, extensive vegetation - mostly beech forest or manuka and gorse scrub - obscures any outcrop and, further inland, extensive weathering makes any study of the structural geology impracticable.

1.3: FIELD WORK

1.3.1: Logistics

Field work was carried out in six two-week field trips to the area. Public transport provided initial access to the Abel Tasman National Park, and accommodation was available in the form of the well-maintained tramping huts and camping grounds in the park. Each trip was based at one or two sites which were accessible by up to a full day's walk along the Coastal Track.

From these sites, day trips were made using the Coastal Track to reach the bays from which it was possible to walk around the headlands that divided the bays. These headlands were typically only accessible within two hours either side of low tide, field work therefore being restricted to four hours each day. However, it was found that almost all the coastline was accessible in this manner, with only the area between Tonga Bay and Awaroa Inlet being impassable (parts of this area were studied thanks to a trip by boat provided by Totaranui-based D.O.C. staff, and the use of an overgrown animal track to Shag Harbour which was shown to me by staff at the Awaroa Lodge).

1.3.2: Field Trip Organisation

The first three field trips were intended as reconnaissance exercises. Each covered a different area: the first from Tata Beach to Separation Point; the second from Separation Point to Bark Bay; and the third from Bark Bay to Kaiteriteri. These trips were intended to determine what structures were normally present in the granite, and to identify local features or areas of interest. Once it was known what sort of features were present for detailed study, a second set of trips, divided as before, were carried out to acquire detailed data over the whole of the field area. Time was set aside to investigate areas of interest thoroughly.

CHAPTER 2

BACKGROUND GEOLOGY

2.1: GEOLOGICAL PROVINCES

New Zealand geology can be divided into two major provinces - the Eastern Province and the Western Province (Fig 1). The Eastern Province consists of a series of amalgamated terranes that have been stitched onto the autochthonous Western Province. The Western Province is interpreted to be a marginal fragment of the Gondwana super-continent that broke away from Antarctica in the Late Cretaceous, and includes the oldest rocks in New Zealand. The two provinces are divided by the Median Tectonic Zone which consists of slivers of fault-bounded arc-related volcanics and plutonics with minor sediments (J. D. Bradshaw, 1993; Kimbrough et al, 1993). New Zealand's granitoid rocks are restricted to the Western Province, and, as it stitches the Median Tectonic Zone to the Western Province, the Separation Point Batholith is the easternmost of these (Tulloch, 1983).

2.2: NEW ZEALAND GRANITOIDS

The granitoids of the Western Province can be divided into distinct batholiths and suites (Tulloch, 1988). Between Nelson and Westport are three parallel NNE-trending batholiths: the western-most Paparoa Batholith; the larger Karamea Batholith; and the eastern Separation Batholith. Further south are the Hohonu and Rangitoto Batholiths. Some of these batholiths, however, are interrelated, and most are internally variable in composition - a division into suites of like composition is more meaningful (Fig 1).

2.2.1: The Karamea Suite

The Karamea Suite makes up the bulk of the Karamea Batholith, most notably including the Karamea Granite, the Dunphy Granite, O'Sullivan's Granite, Whale Creek Granite, and the Zetland Diorite. It also includes small isolated plutons such as those at Meybille Bay and Barrytown. All of the granitoids within this suite have crystallisation dates within a 375 ± 5 Ma age range (Muir et al, 1995b).

The tectonic conditions at the time of the emplacement of the Karamea Suite are unknown. Correlation with Paleozoic magmatism in SE Australia, Tasmania and Antarctica has been proposed by Muir et al (1995b), with continental reconstructions suggesting the presence of a 2000 km long belt of magmatic activity along the Paleo-Pacific margin of Gondwana. However, although many of the geochemical characteristics suggest that these are subduction-related magmas, there is no evidence of subduction in the region at the time of their emplacement, and much of the evidence is ambiguous.

2.2.2: Hohonu Supersuite

The mid-Cretaceous (114 to 109 Ma) Hohonu Supersuite is composed of three contemporaneous suites: the Rahu Suite, which makes up most of the Paparoa Batholith; the Te Kianga Suite, a similar highly evolved I/S-type granitoid; and the more mafic I-type Deutgam Suite (Waight, 1995).

The supersuite dominates the Hohonu and Paparoa Batholiths, as well as contributing to the Karamea Batholith (Tulloch, 1983 & 1988).

Being even further inboard of the contemporary Pacific continental margin than the Separation Point Batholith at the time of their intrusion, these granitoids are not considered to have been generated as normal subduction-related magmatic rocks. Instead, they are considered to have been generated shortly after the end of the compressive regime associated with this subduction (see Chapter 7). Relaxation and crustal thinning of the thickened crust led to adiabatic melting of the lower continental crust as a result of isothermal uplift (Waight, 1995).

2.2.3: Fiordland Granitoids

The geochemistry of the Separation Point Batholith has been correlated with that of some of the Fiordland granitoids from the south-west corner of the South Island (Muir et al, 1992), these having been displaced from the NW Nelson region by Cenozoic movement along the Alpine Fault (Fig 1). Fiordland geology is marked by the juxtaposition of high grade metaplutonic and metasedimentary rocks in the west against relatively undeformed plutonics in the east (Oliver & Coggan, 1979). The western rocks are dominated by the Western Fiordland Orthogneiss - granulite facies dioritic rocks - which intrude the older Central Fiordland metasediments (J. Y. Bradshaw, 1990) of similar grade. These high grade rocks are bounded to the east by the Surprise Creek Fault, a major tectonic break which separates them from the low grade Eastern Fiordland igneous belt (Fig 1).

Based on geochemical similarities, the Western Fiordland Orthogneiss appears to be an earlier (c. 120 Ma) deeper crustal level intrusion of magma from the same source as the Separation Point Batholith (Muir et al, 1992, 1995a). Under the compressive regime active at the time (Muir et al, 1995a; Waight, 1995) the emplacement occurred under, or was soon followed by, granulite facies conditions. During the following period of late-Cretaceous extension, the Western Fiordland Orthogneiss was uplifted and unroofed (Gibson et al, 1988), their cover rocks now displaced to the east. These cover rocks, the relatively undeformed Eastern Fiordland igneous belt, include upper crustal granitoids which have also been correlated with the Western Fiordland Orthogneiss on the basis of geochemistry and geochronology (Muir et al, 1995a).

2.3: COUNTRY ROCKS

2.3.1: Arthur Group

The Separation Point Batholith intrudes older rocks of the Takaka Terrane, including the sedimentary Mount Arthur and Ellis Groups and the Riwaka Igneous Complex (Grindley, 1971 & 1980; Coleman, 1981).

The Mount Arthur Group is dominated by the Arthur Marble, which, although visibly fossiliferous and of low metamorphic grade elsewhere, is more strongly metamorphosed nearer to the contact with the Separation Point Batholith. This formation is Ordovician in age, and consists of marble interbedded with minor schist and quartzite. Skarn mineralisation is developed close to intrusive contacts.

Underlying the Arthur Marble is the Pikikiruna Schist, which is upfaulted along the sheared margin of the Separation Point Batholith. These amphibolite facies pelitic and quartzitic rocks show a prominent to coarse foliation. The uppermost formation in the Mount Arthur Group is the Wangapeka Formation, consisting of pelitic and quartzitic rocks with an upper calcareous and fossiliferous facies. Greenschist facies metamorphism and deformation have led to the development of a slaty cleavage. It is Late Ordovician to Late Silurian in age.

2.3.2: Ellis Group

Overlying the Mount Arthur Group is the Ellis Group, which includes the Hailes Quartzite and its metamorphic equivalent, the Onekaka Schist. The Hailes Quartzite is a thick (1200 m) unit of quartz sandstone and quartzite of Silurian age. The Onekaka Schist consists of biotite schists and quartzites and minor amphibolite.

2.3.3: Riwaka Igneous Complex

The Riwaka Igneous Complex is a middle-late Devonian mafic to ultramafic intrusive complex outcropping as an elongate body along the western margin of the Separation Point Batholith, south of Takaka Hill. In Riwaka Valley it has been metamorphosed to an amphibolite from gabbros and pyroxene diorites, and is strongly foliated around the margins. Further south, the complex can be divided into three units: the massive Campbell Gabbro, which forms the central part; the Pokororo Pyroxenite, a 1 kilometre wide dike-like body of cumulate olivine pyroxenite with serpentinised layers of dunite; and the Brooklyn Diorite, a two-pyroxene biotite diorite which intrudes the Onekaka Schist and which is the most felsic fractionation product of the complex. Along the north-western boundary of the Separation Point Batholith is a smaller mafic pluton known as the Rameka Diorite, which is also considered to be part of the Riwaka Igneous Complex.

A K-Ar hornblende age of 370 Ma from the Rameka Gabbro (Harrison & McDougall, 1980) and an Ion Microprobe Zircon age of 377 Ma from the Brooklyn Diorite (Muir et al, 1995b) show the complex to be coeval with the Karamea Suite, although its relatively primitive isotopic composition and its spatial isolation from the Buller Terrane, to which the Karamea Suite is limited, suggests that any real correlation is improbable.

2.4: PREVIOUS WORK ON THE SEPARATION POINT BATHOLITH

2.4.1: Geological Mapping

Mapping of the Takaka and Cobb regions by Grindley (1971 & 1980), and of the Wangapeka by Coleman (1981), showed the Separation Point Batholith to be an elongate body outcropping from Separation Point in the north to Mt Murchison in the south - a total length of approximately 120 km. It is broken into three segments of approximately equal size, and has an average width of around 10 km (Fig 1).

They identified several different units within the Separation Point Batholith: the Wainui Quartz Diorite; the Canaan Granodiorite; the Onahau Granite; the Pearse Granodiorite; and the Rocky Granodiorite. The majority of the granite is described as a composite batholith ranging in composition from quartz diorite in the north-east through biotite-hornblende granodiorite to biotite leucogranite along the east coast of the Abel Tasman National Park and south of Motueka.

The Wainui Quartz Diorite, which outcrops along the western margin of the batholith north of the Motueka-Takaka Road, is described as ranging from quartz diorite to minor gneissic granite, and as being strongly foliated with steep down-dip lineations. Grindley interprets this western boundary to be a significant structural feature which he names the Wainui Shear Zone.

The Canaan Granodiorite forms two irregular bodies west of the Wainui Shear Zone, intruding Mount Arthur Group metasediments and Riwaka Intrusives. Hornblende dominates in the northern body, but biotite dominates the southern body which is described as granitic in composition.

The isolated Onahau Granite forms a pluton west of Takaka, intruding the Mount Arthur Group. Described as a medium-grained leuco-adamellite, it contains accessory garnet, which is also present in aplite dikes along with muscovite and tourmaline.

The Pearse and Rocky Granodiorites outcrop as large plutons of approximately 100 km^2 and 25 km^2 size respectively. They are located approximately in the middle of the batholith, producing gradational contacts with the Separation Point Granite. Field relationships suggest that the Pearse Granodiorite is the youngest.

2.4.2: Geochemical Studies

A study by Harrison & McDougall (1980) of the Rameka Diorite and the Separation Point Batholith yielded information on the cooling history of the Separation Point Batholith. The study was based on the comparison of mineral ages from samples of the Rameka Diorite taken at varying distances from the contact with the Separation Point Batholith.

Their research found that the Separation Point Granite was emplaced at 780°C at a pressure of 2 - 5 kbars. They estimate the depth to have been from 6 to 12 km. The intrusion raised country rock temperatures, including the Rameka Diorite, to 590°C near the contact, although this fell away to 505°C 2.5 km from the contact. 5 km away, the effect was thought to be a minimal increase of only 50° from the ambient temperature of ~370°C.

In preparation for developing a heat flow model for the intrusion, they determined that the porosity and water content precluded the possibility of heat transfer by convection in the Rameka Diorite, their model subsequently being based on transfer by conduction. This model matched the data acquired from the mineral age dating, thus supporting the assumptions made to define the model's variables. These assumptions include: uplift of the granite to 3 km depth by ~100 Ma; cooling of the granite to 120°C over the same period; and a thermal gradient of 40°C km^{-1}.

More recent geochemical studies have been carried out by Muir et al (1994a, 1995a), and have provided new information relating to the genesis of the batholith. They are therefore further discussed under

Chapters 7 and 8. The most reliable dates for the Separation Point Batholith have recently been determined by SHRIMP U-Pb zircon dating by Muir et al (1994b). This study gave 118±3 Ma for the crystallisation age of the batholith.

CHAPTER 3

PEGMATITES AND APLITES

3.1: INTRODUCTION

Throughout the investigation of the Separation Point Batholith, pegmatite and aplite dikes were studied in detail, and recorded in field notes, field sketches and photographs. This study was intended to identify and document the occurrence of the various complex features of aplites and pegmatites in the area, as identified elsewhere (eg Cameron et al, 1949; Jahns, 1955). Although pegmatite and aplite dikes can provide additional structural information (eg Marre, 1986; Brisbin, 1986), collecting a representative set of data of their attitude and structural orientation proved impracticable. Over even a small stretch of coastline there could be hundreds of pegmatite and aplite dikes, and, although it was apparent that there was a preferred orientation (most typically close to horizontal), it would have required the measurement of the attitude of most of these to get a reasonable numerical value to represent this orientation.

3.2: PREVIOUS WORK

3.2.1: Common Features of Aplites and Pegmatites

There are many unusual features which commonly occur in aplite and pegmatite dikes. These features include layering, zoning, compositional segregation, and textural contrasts. All of these features must be considered in any model for the genesis of pegmatites and aplites.

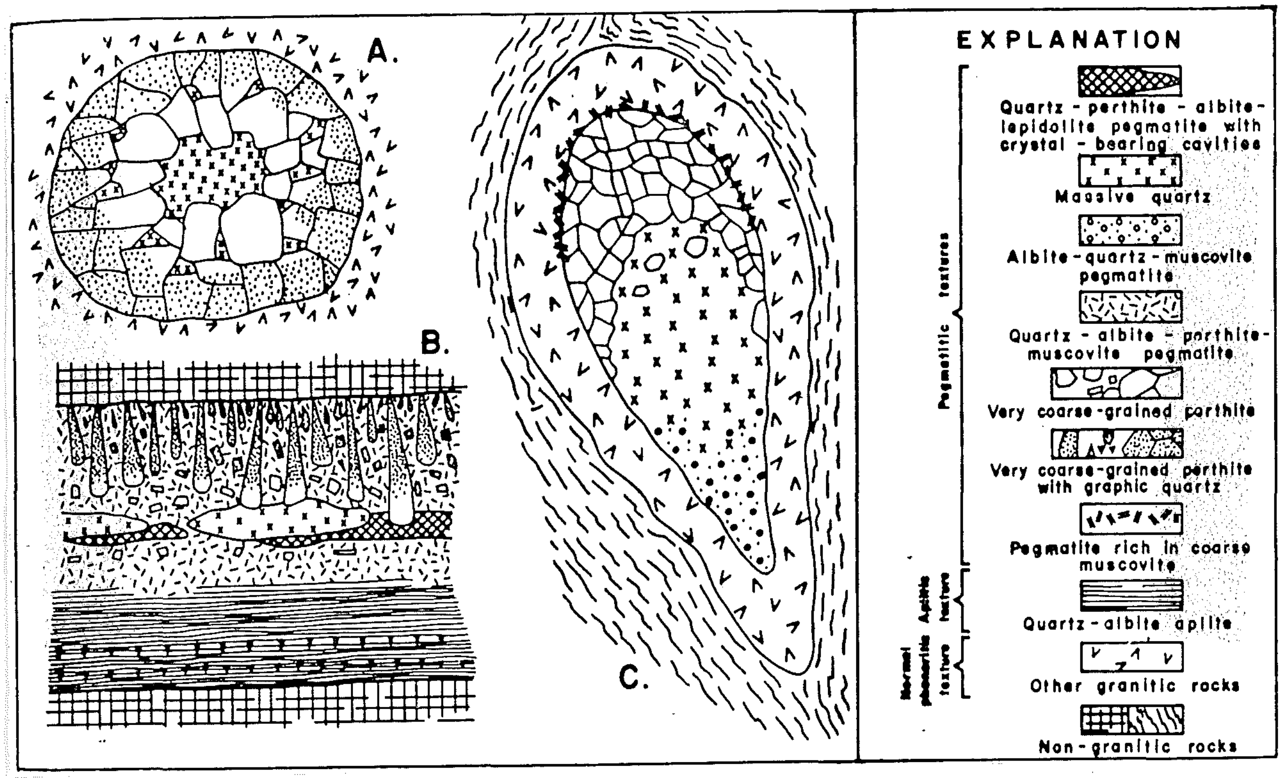


Fig 2: Diagrammatic vertical sections illustrating three kinds of segregation in bodies of pegmatite at contrasting scales.
A. Symmetrically zoned miarolitic pod in a granite. Diameter measured in inches.
B. Asymmetrically zoned pegmatite dike with aplitic footwall portion. Thickness measured in feet.
C. Asymmetrically zoned pod-like body of pegmatite with granitoid outer portion. Thickness measured in tens of feet.
From Jahns & Burnham (1969, Fig 5).

The most common feature of pegmatites is zoning. Zones form successive shells, approximately parallel to the pegmatite walls, and are defined by variations in composition and/or texture (Cameron et al, 1949; Jahns, 1955). Almost always present is a border zone or selvedge of fine-grained material which separates the rest of the pegmatite from the country rock. Cores of quartz are also very common, although these central zones are rarely continuous, often forming pods of quartz at irregular intervals where the pegmatite is thickest (Cameron et al, 1949). Intermediate zones, concentric to the cores and parallel to the margins, make up the rest of the body, and may number from one to five or more. Although zones are normally described as concentric and semi-symmetric, they may be incomplete or favour the upper or lower half of a body (Fig 2).

Compositional segregation occurs in asymmetrically zoned pegmatites, where zones of different composition are not concentrically distributed (Fig 2). Such segregation usually involves the concentration of potassium feldspars near the top of such bodies, while albite is concentrated towards the bottom (Jahns & Tuttle, 1963; Jahns & Burnham, 1969; Stern et al, 1986; Duke et al, 1992).

Extreme textural contrasts sometimes occur, particularly in those bodies which include both aplite and pegmatite. Often associated with the compositional segregation of potassium feldspar and albite is the occurrence of coarsely pegmatitic material overlying layered aplitic material (Cameron et al, 1949; Jahns & Tuttle, 1963; Jahns & Burnham, 1969; Stern et al, 1986; Duke et al, 1992; Fig 2). Examples where aplitic material is found sandwiched between an upper and lower layer of pegmatite are also known (Jahns, 1955; Jahns & Burnham, 1969).

Aplites generally do not display as much internal complexity as pegmatites do, the most common feature being a fine layering (Jahns, 1955; Jahns & Tuttle, 1963; Stern et al, 1986; Duke et al, 1992). This layering varies in thickness from a few millimetres to a few centimetres, and is caused by small variations in composition. This compositional variation is sometimes highlighted by fine, millimetre thick layers of garnet or tourmaline, to produce what is known as 'line-rock'(Jahns, 1955; Jahns & Tuttle, 1963; Stern et al, 1986).

3.2.2: Models of Pegmatite and Aplite Genesis

Many workers have presented models for the genesis of pegmatites and aplites (see Jahns, 1955, for an extensive review), but the model put forward by Jahns & Burnham (1969) was the first to adequately explain the majority of the unusual features of pegmatites. In this model, the pegmatite magma is crystallised under closed conditions, and the initial crystallisation of primarily anhydrous phases leads to a build up of H_2O in the remaining melt (H_2O is effectively an incompatible component). The model proposes that the concentration of H_2O becomes so great that it over-saturates the melt, and a separate hydrous phase is eventually exsolved. This hydrous phase is much lower in viscosity than its host magma, resulting in high diffusion rates which in turn allows large crystals to form.

This model has been almost universally adopted, and several workers have found the model useful when investigating pegmatite occurrences (eg Stern et al, 1986; Walker et al, 1986; Shearer & Papike, 1992).The model explains the occurrence of the fine-grained wall zones (crystallised under sub-critical conditions), has been modified to explain intermediate zoning due to buffering "facilitated by the rapid transport capabilities of a co-existing fluid phase" (Walker et al, 1986), and explains the compositional and textural contrasts by segregation and migration of the hydrous phase (see discussion below). Further experimental (eg Burnham & Nekvasil, 1986) and field investigations (eg Duke et al, 1992) have added more information about the nature of the different phases during pegmatite formation.

However, the actual presence of a separate aqueous phase has never been adequately established, either in the field or experimentally. Some workers (most notably London, 1992) propose that the growth rates of pegmatite magmas are high enough (eg 10^{-7} cm/s, or 31.5 cm per year, Fenn, 1977), given the under-cooled conditions of pegmatite emplacement, and that the presence of relatively small quantities of H_2O act simply to decrease nucleation density within the melt. They therefore suggest that it is possible to achieve the coarse textures of pegmatites without necessarily requiring an exsolved hydrous phase. However, this model does not explain the many other complexities which are so often present in pegmatites.

Aplites and pegmatites are clearly closely related - they have very similar compositions, are emplaced under structurally similar conditions, and sometimes occur combined in a single body. This may seem odd when the difference between them is considered: aplites are very fine grained when compared to the bulk of the granite; whereas pegmatites are very coarse grained. This is because aplites represent pegmatitic magma which has crystallised in the absence of an exsolved hydrous phase (Jahns & Burnham, 1969), and therefore have not developed a coarse, pegmatitic texture. In fact, because they are emplaced as small intrusive bodies, they are cooled a lot more quickly than the larger volumes of magma, and therefore produce a fine-grained texture.

Figure 3: Hornblende-bearing pegmatite from Tata Beach.

Figure 4: Simple pegmatite displaying fine grained wall zone and coarser intermediate zone.

3.3: DESCRIPTION OF APLITES AND PEGMATITES

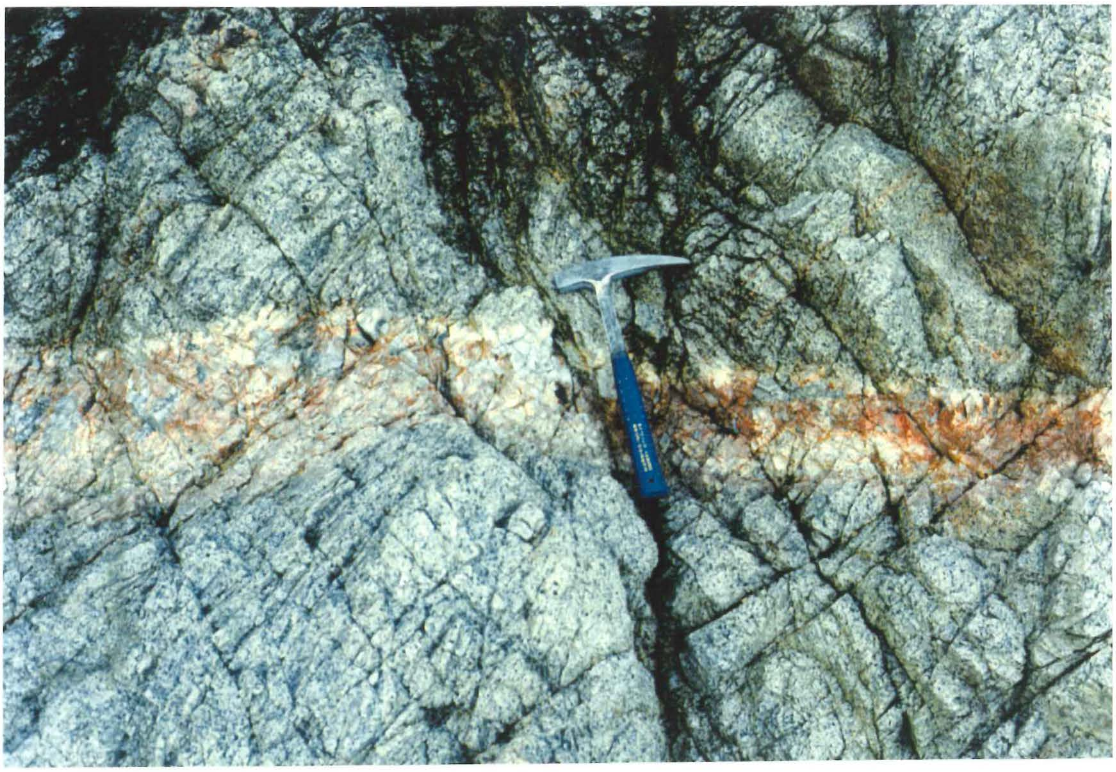
3.3.1: Mineralogy

The pegmatites and aplites of the Separation Point Batholith are typically granitic in composition, with quartz, potassium feldspar and plagioclase always present in varying ratios (Fig 5). Precise compositions are difficult to derive, particularly in pegmatites, because variations frequently occur over very small distances. The only way an accurate composition could be determined is to sample an entire body - an exercise well outside the limits of this project.

The pegmatites and aplites are remarkably poor in mafic minerals, the most abundant such mineral being biotite. However, even biotite typically makes up less than 1% of these rocks. The pegmatites outcropping on the headland at Tata Beach are something of an exception. The cores of these pegmatites are made up of hornblende and quartz (Fig 3), and, in small pegmatite pods, the hornblende content easily exceeds 50% (Fig 17). Pyrite crystals were also seen in some examples. Garnet is another accessory mineral, seen in aplites between Awaroa Inlet and Tonga Bay forming 'line-rock' in a series of thin (< 5 mm) bands paralleling each other and the sides of the aplite.

3.3.2: Internal Structure

The aplites typically have a very simple structure, forming tabular intrusive sheets extending for many metres. Thickness is extremely variable ranging from one or two centimetres to composite bodies up to 5 metres thick. Grain size is fine, rarely exceeding 2 mm, producing a



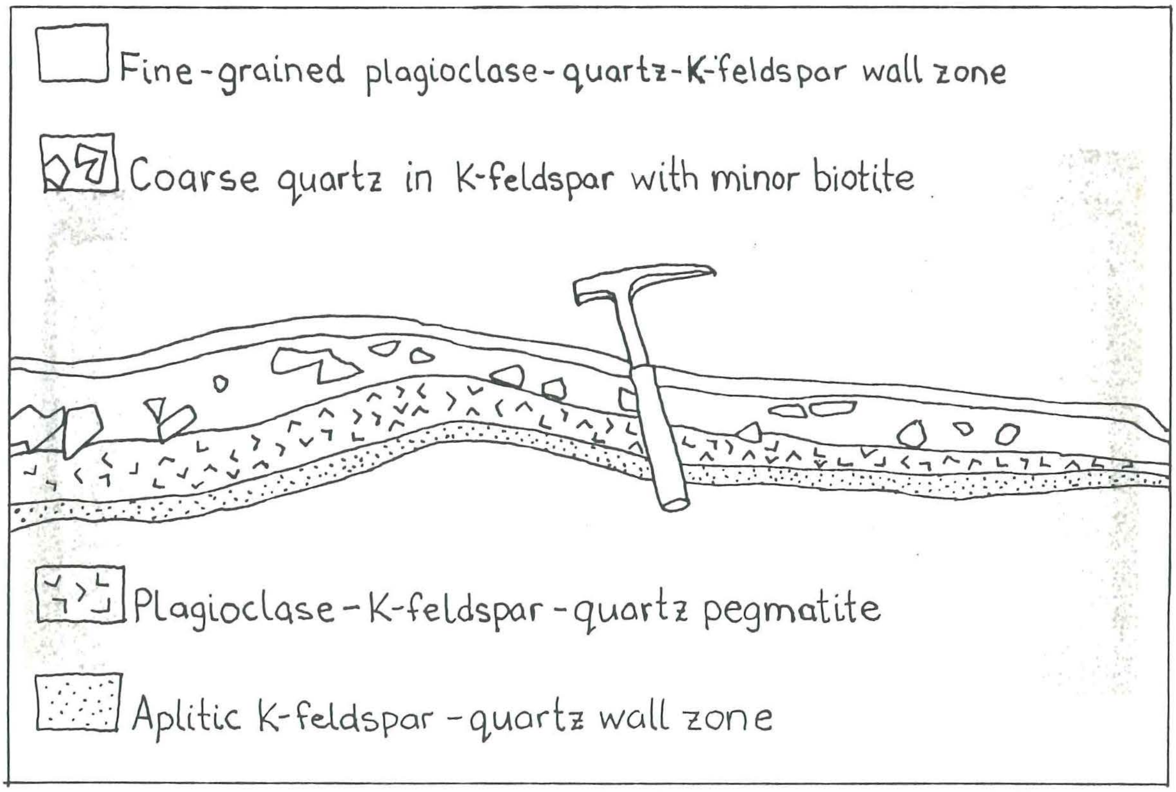


Figure 5: **Zoned pegmatite with fine-grained wall zones and two intermediate zones**

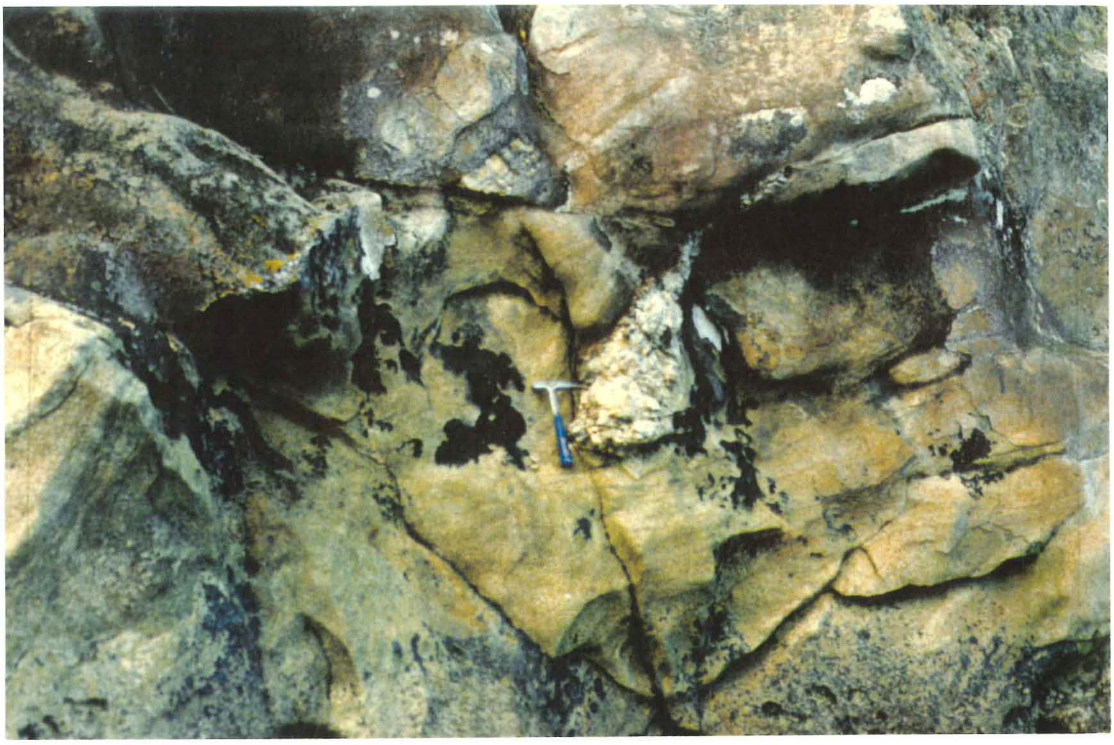


Figure 6: Pod-shaped pegmatite.

Figure 7: Lenticular pegmatite, asymmetrically zoned. In this unusual case, the upper zone is rich in plagioclase, while the lower zone is rich in coarse potassium feldspar.

distinctive sugary texture. In some examples, aplites display a banded appearance caused by small variations in composition (Fig 9). This structure is probably formed by repeated discrete episodes of crystallisation, and in some cases may represent repeated magmatic intrusion. These composite bodies are especially apparent where some layers are defined by small bands of pegmatitic material.

The majority of the pegmatites in the field area have a similar structure to the aplites. These intrusive sheets are also extensive, rarely having both ends outcropping along the shore platform. Thickness ranges from a few centimetres to about 10 cm before complex zoning develops. Crystal size varies from about 1 cm to 5 cm. The only internal structure is usually the presence of a finer grained wall zone separating an inner intermediate zone from the margins (Fig 4).

Pegmatites with a thickness in excess of approximately 10 cm tend to exhibit more complex internal structures. External shape is also more variable, with some bodies forming less extensive pods or lenses, sometimes less than 1 metre across (Fig 6 & 7). The internal structure normally takes the form of zones which develop approximately parallel to the pegmatite boundaries. These zones are defined by variations in composition or crystal size (Fig 5). The most common zoning present is the occurrence of a thin (< 3 cm) fine grained wall zone. Also common are a discontinuous series of quartz pods in the middle of the pegmatite, known as the quartz core. Between these two zones are a variable number of intermediate zones which may be repeated both sides of the

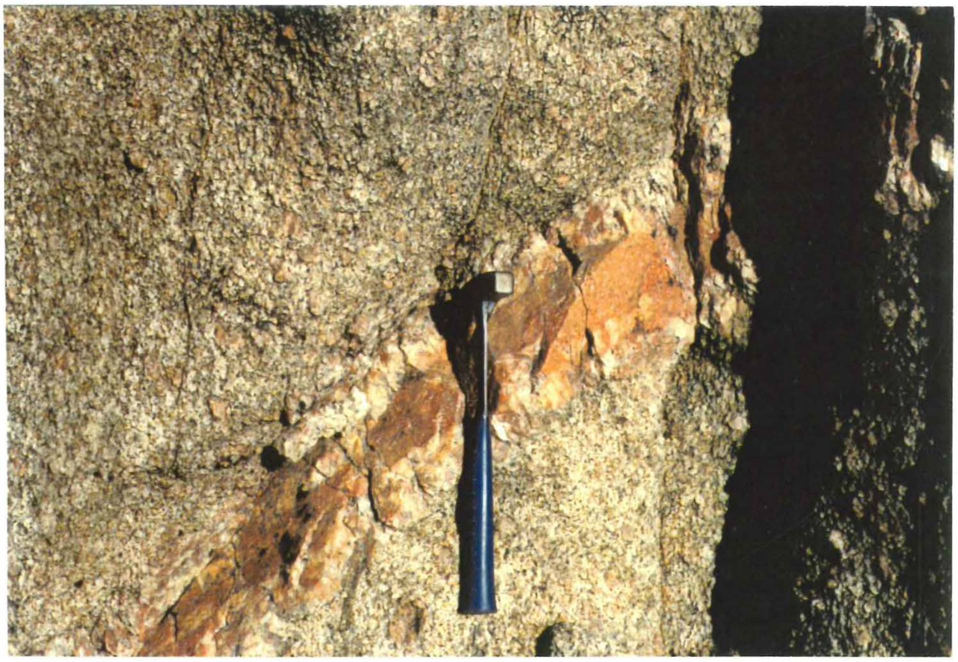


Figure 8: Pegmatite shell filled with aplite.

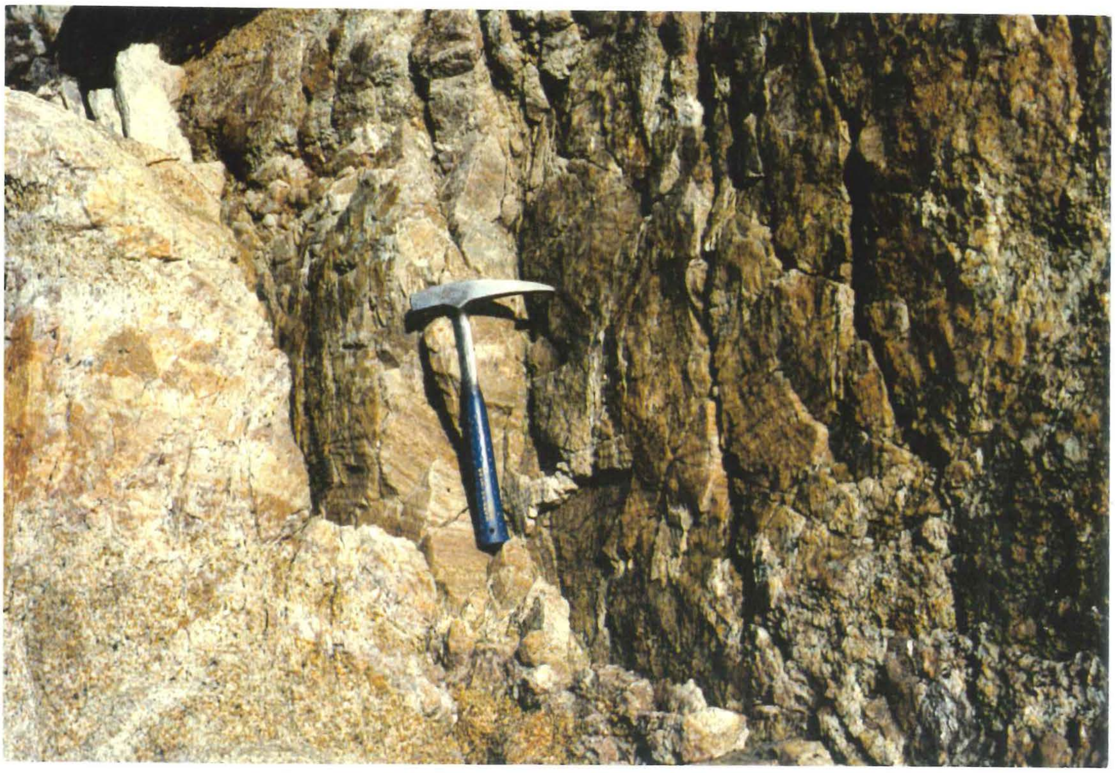


Figure 9: Banded aplite with thin pegmatitic margin.

quartz core, or may occur only above or below. In pod or lens shaped pegmatites, these zones are often concentric about the quartz core.

3.3.3: Combined Aplite/Pegmatite Bodies

The presence of a hydrous phase is critical in the development of pegmatitic texture (Jahns & Burnham, 1969), as is evidenced by the presence of combined pegmatite-aplite bodies. The most common such occurrence is a result of the loss of internal pressure in the crystallising pegmatite body. This is caused by the loss of the hydrous fluid into the surrounding host through fractures or other paths and instantly reduces the diffusion rates to those typical of an aplitic body. Without a return to a closed system, the result is a pegmatitic shell filled with fine-grained aplite (Fig 8 & 9).

Fig 10: Pegmatite overlying aplite.

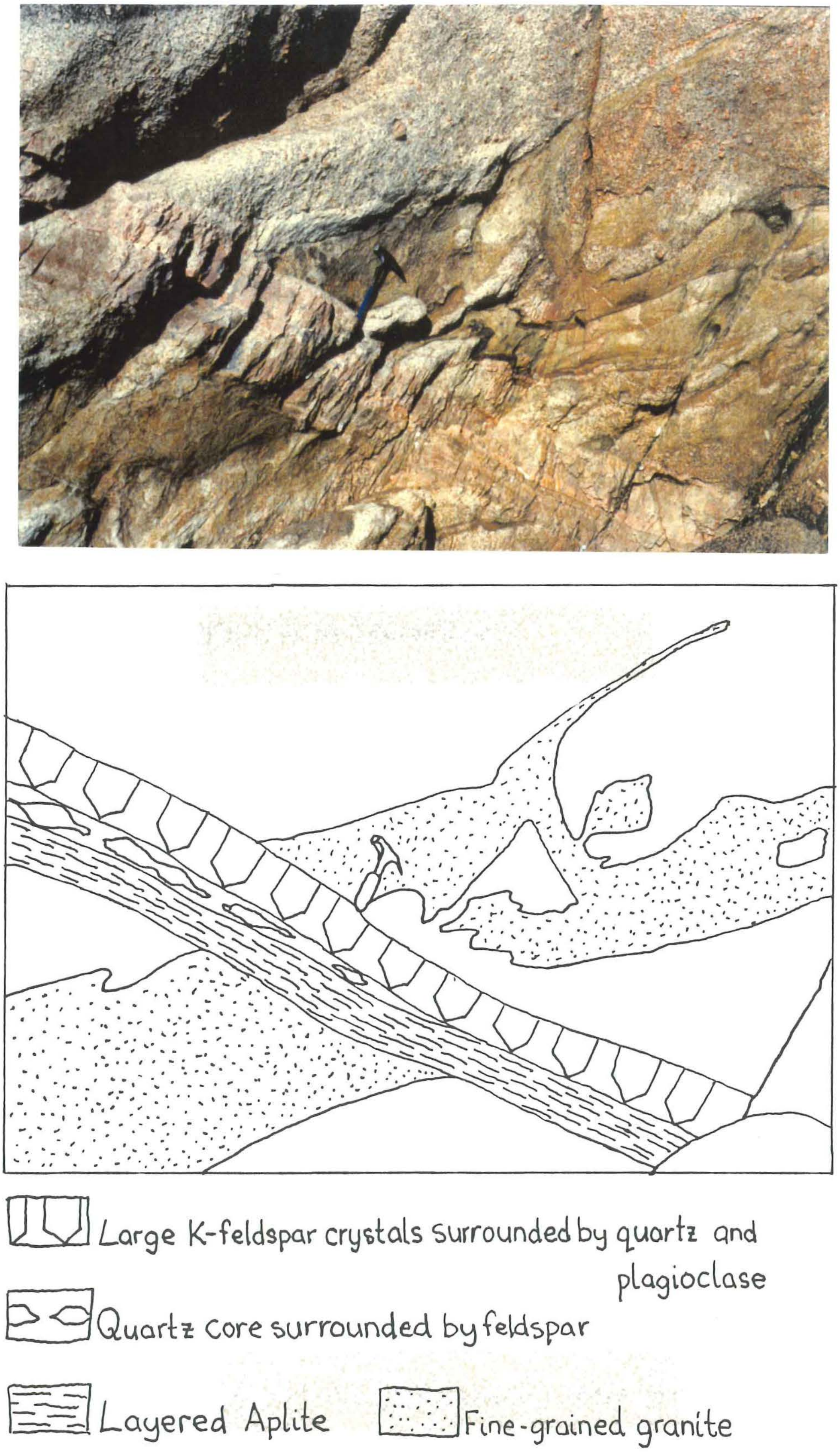


Figure 11: Asymmetrically zoned pegmatite with coarse potassium feldspar above a quartz-feldspar core, and with banded aplite below.

Another variation occurs due to the low density of the hydrous phase. In some bodies this phase may concentrate near the top, so that the upper half crystallises as a pegmatite, while the lower half crystallises as an aplite (Fig 10 & 11). This also often leads to a compositional layering due to the difference in partition coefficients for components in the hydrous and magmatic phases. A partitioning between potassium (favouring the hydrous phase) and sodium (favouring the magmatic phase) is particularly common (Jahns & Burnham, 1969; Stern et al, 1986).

3.4: EXCEPTIONAL PEGMATITE OCCURRENCES

3.4.1: Reef Point to Wharf Rock Pegmatites

North of Tonga Bay, between Reef Point and Wharf Rock, the pegmatites have developed a particularly coarse texture, and some potassium feldspar crystals exceed 20 cm in length (Fig 12 & 13). This texture seems to have developed in response to the shape of the pegmatite bodies, which is more irregular than the normally simple tabular sheets which occur throughout most of the batholith.

These pod-like or lenticular pegmatites appear to have larger central zones which remained as closed systems during crystallisation, leading to the development of a more stable hydrous phase than in the thinner tabular sheets. The presence of this hydrous phase over the extended period of time it would take for these thicker bodies to crystallise would lead to the development of the particularly coarse pegmatitic texture observed.

Figure 12: Exceptionally coarse pegmatite. Large potassium feldspar crystals with quartz and plagioclase matrix.

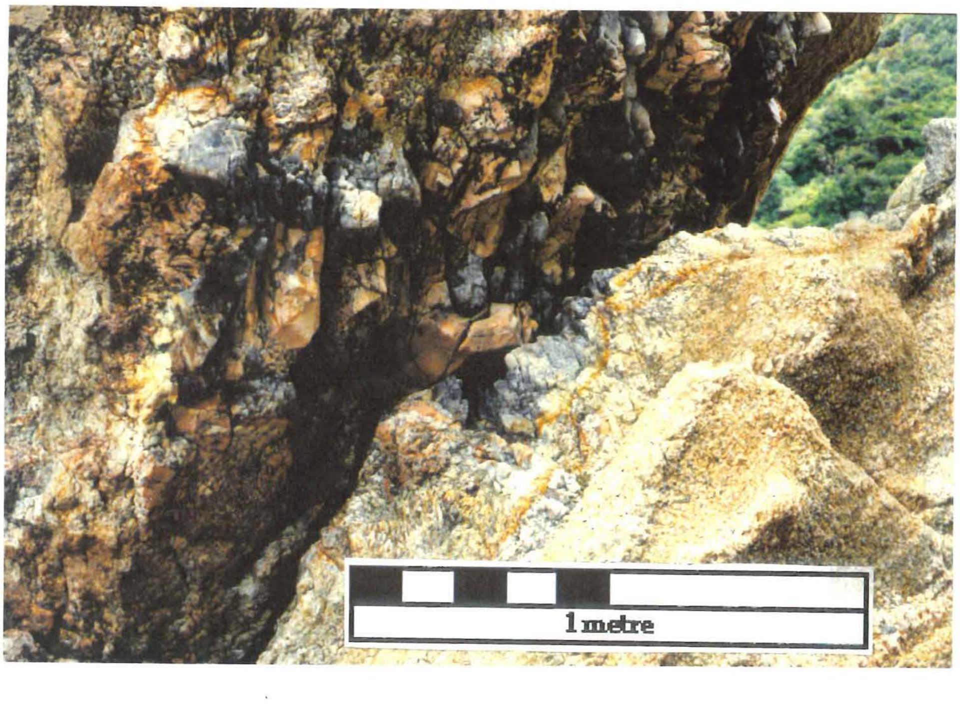


Figure 13: Exceptionally coarse potassium feldspar-quartz pegmatite.

3.4.2: Shag Harbour Aplite Complex

A little further north, near Shag Harbour, an unusually thick sequence of layered aplites and pegmatites occurs. This sub-horizontal sequence is up to 6 metres thick, and consists mainly of finely banded aplites, separated by thin (up to 10 cm) pegmatitic selvedges (Fig 14). There seems to have been a plane of weakness along which multiple intrusions of late-stage magma occurred, and in which a closed system for crystallisation was impossible to maintain. As a result, only early development of pegmatitic material could occur before the system became open and loss of the hydrous phase led to the remaining material crystallising with an aplitic texture.

3.4.3: Waiharakeke Beach Quartz Crystal

Another occurrence of coarse pegmatite is found at the north end of Waiharakeke Beach. Set in the granite just beneath a small (10 cm thick) pegmatite is an excellent cross-section of a prismatic hexagonal quartz crystal more than 20 cm across (Fig 15). Pieces of coarse alkali feldspar are attached to the crystal, but no further evidence of coarse pegmatite occurs near it. It appears to have been ripped from its parent pegmatite body and carried as an enclave within the granite.

3.5: STRUCTURAL RELATIONSHIPS

The structural relationships between pegmatite and aplite dikes and their hosts tend to be somewhat ambiguous. The dikes are clearly late stage intrusives relative to the bulk of the granite, but in some places more complex relationships are apparent.

Figure 14: Thick sequence of banded aplites with thin pegmatite layers. Photo shows approximately half the thickness of the sequence.

Figure 15: Large, isolated quartz crystal. Waiharakeke Beach.

Many pegmatites are found filling joints in the granite, obviously finding these structures suitable planes of weakness along which they can intrude. However, in some areas, jointing can be seen to cut through pegmatites, and is often particularly well defined in the finer grained aplite dikes. In areas where there are several phases of magmatic material and where magma mixing occurs, similarly ambiguous relationships occur (Fig 18 & 20) Late (often mafic) magma can be seen intruding earlier granite and its pegmatites, and is then, itself, cut by still later granitic pegmatites.

The best interpretation of the relationships displayed is that the intrusion of the pegmatite and aplite dikes is not a separate late stage process relative to the emplacement of the Separation Point Batholith, but is essentially a simultaneous process, producing features in most cases only slightly younger than that of the host rocks. Hence, other features which form soon after the emplacement of the bulk of the magmatic material, such as jointing, foliation and lineation, and late stage magma mixing and intrusion, will share varying structural relationships with the pegmatites and aplites according to the local timing of their generation.

3.6: CONCLUSIONS

- The pegmatites of the Separation Point Batholith are typically granitic in composition, with quartz, alkali feldspar and plagioclase being the dominant minerals.

- Most aplites and pegmatites form extensive tabular sheets. The aplites occasionally display banding, while most pegmatites display only simple zoning.
- Pegmatites in excess of 10 cm thickness tend to be more irregular in shape and exhibit more complex zoning.
- Aplite and pegmatite sometimes form part of the same body, most typically as a pegmatite shell filled with aplite, or as a pegmatite layer above an aplite layer.
- These features are typical of the complexities of pegmatite and aplite bodies, and are best explained with reference to the Jahns-Burnham model.
- Pegmatite and aplite genesis and emplacement are essentially simultaneous with the emplacement of the batholith, and overlap with the development of other late stage features.

CHAPTER 4

MAGMATIC HETEROGENEITIES AND ENCLAVES

4.1: INTRODUCTION

Most of the Separation Point Batholith is remarkably homogeneous, and maintains a consistent composition over large areas. Local, small scale variations such as patches of accumulated potassium feldspar megacrysts, albitised lenses and biotite clots and concentrations do occur, but only on a metre scale. Over the batholith as a whole, there is also a gradational zoning from biotite monzogranite on the east coast to hornblende-biotite granodiorite west of Whariwharangi.

However, there are two areas where significant heterogeneity is visible on the outcrop scale; this chapter describes and discusses these areas. Enclaves are small scale but ubiquitous magmatic heterogeneities in the Separation Point Batholith, and a discussion of their origins is also included here.

4.2: MARGINAL MAGMA MIXING

The coastal exposure of the north-western boundary of the batholith reveals the presence of complex magma mixing and mingling along the margin. The exposures occur along the edge of a small (~300 m across) headland which extends into Ligar Bay, and are accessible from the western end of Tata Beach.

Most of the headland is composed of highly strained rock of granitic composition which appears to be intruded by and mixed with a more mafic magma of dioritic composition, this mafic rock making up around 30 - 40% of the outcrop (see Chapter 6 for a more detailed description). The complexity of their interrelationships makes relative timing of emplacement uncertain, but the mafic rocks typically occur in irregular sheet- or dike-like bodies often tens of metres across, whereas the granitic bodies tend to be more massive (Fig 16).

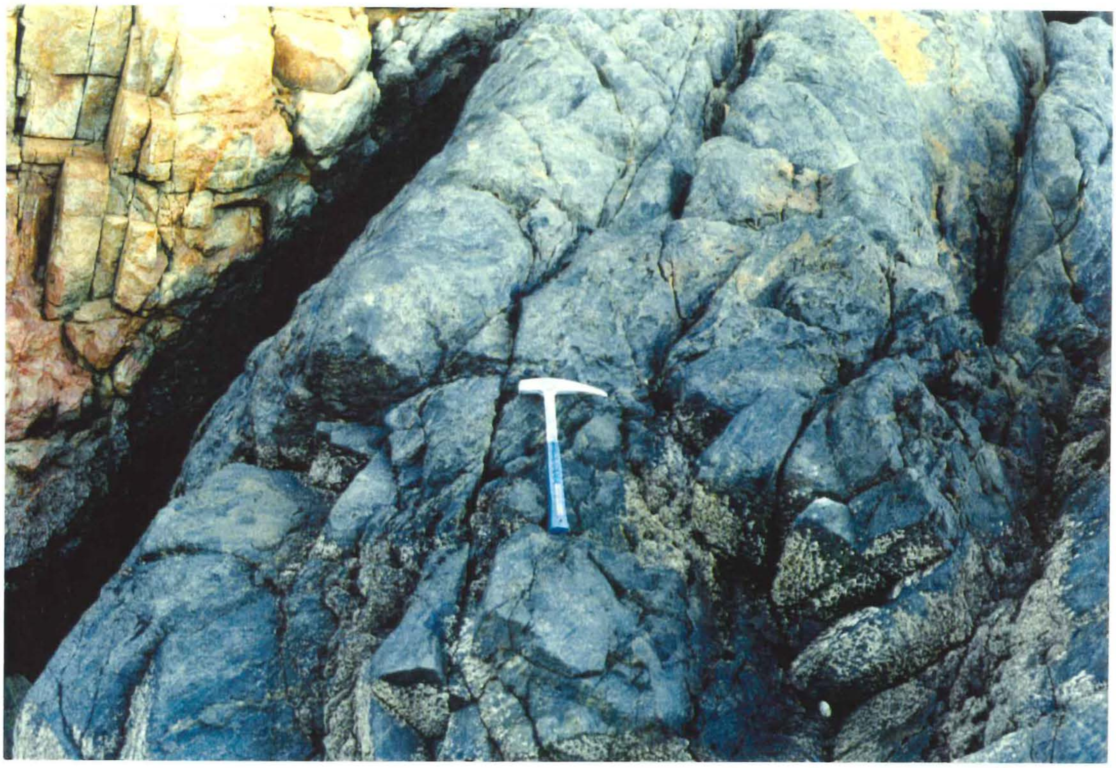


Figure 16: large dike-like body of diorite at Tata Beach intruding uncontaminated granite. Enclaves are faintly visible in the diorite, aligned from top-right to bottom-left. Location of sample SP37 (Fig 33).

The dioritic rocks are obviously a minor phase within the batholith, and it is unknown whether they represent a poorly differentiated but cogenetic variety of the Separation Point Granite, or a separate, possibly mantle-derived magma. The dioritic rocks have undergone significant hybridisation with the granitic magma, and close investigation shows

Figure 17: Hornblende-rich pegmatite cutting hybrid rocks at Tata Beach. Note the many extremely elongated enclaves and foliation running from top-right to bottom-left.

Figure 18: Hybrid rocks from Tata Beach cut by granite pegmatite, both of which are then cut by fine-grained mafic dike (sample SP6, Fig 35).

that even the most mafic dikes contain fine-grained, still more mafic enclaves within them (Fig 17). In contrast, the larger bodies of granitic rock show no sign of mafic contamination. The purest mafic rocks appear to be those that form small (5 - 20 cm) fine-grained dikes that cut through both mafic and granitic rocks, and even the granitic pegmatites (Fig 18 & 35).

It appears that the mafic magma has been in some way concentrated or trapped along the margins of the batholith, and has mingled with the more dominant granitic magma. The fine-grained dikes appear to represent the late-stage intrusion of the remaining relatively uncontaminated mafic magma.

4.3: INTERNAL HETEROGENEITIES

Another area of magmatic heterogeneity occurs between Anchorage and Observation Beach, but, in contrast to the Tata Beach example, only small quantities of mafic magma are involved (Fig 19 & 20). Instead, finer-grained granitic magma is seen to intrude larger masses of coarser granite. The fine-grained granite appears to have intruded as irregular sheets and dikes in much the same manner as at Tata Beach, and is often associated with aplites or pegmatites and small, apparently accessory bodies of mafic magma intruded with it (Fig 21 & 22).

The complexity of the interrelationships again makes it difficult to determine what the origins of the contrasting magmas are, but the unusual features seem to indicate that this area is the zone of mingling between two contemporary plutons (similar to examples in Marre, 1986;

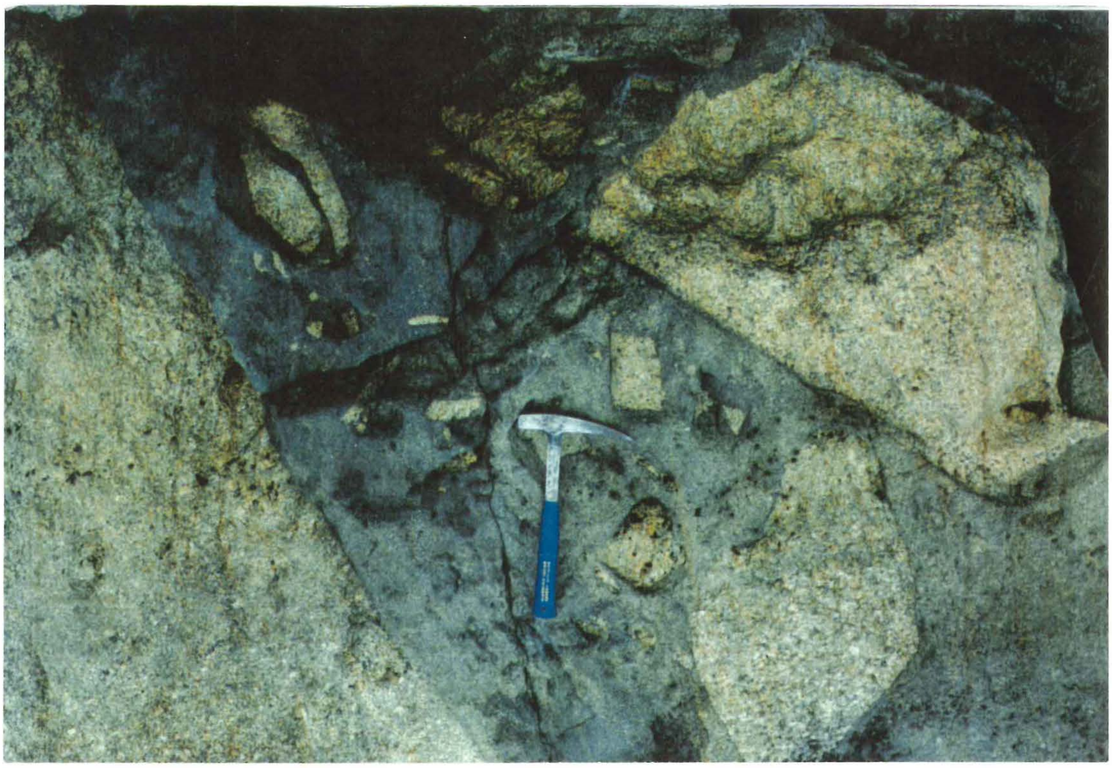


Figure 19: Mafic dike cutting granite, east of Anchorage.

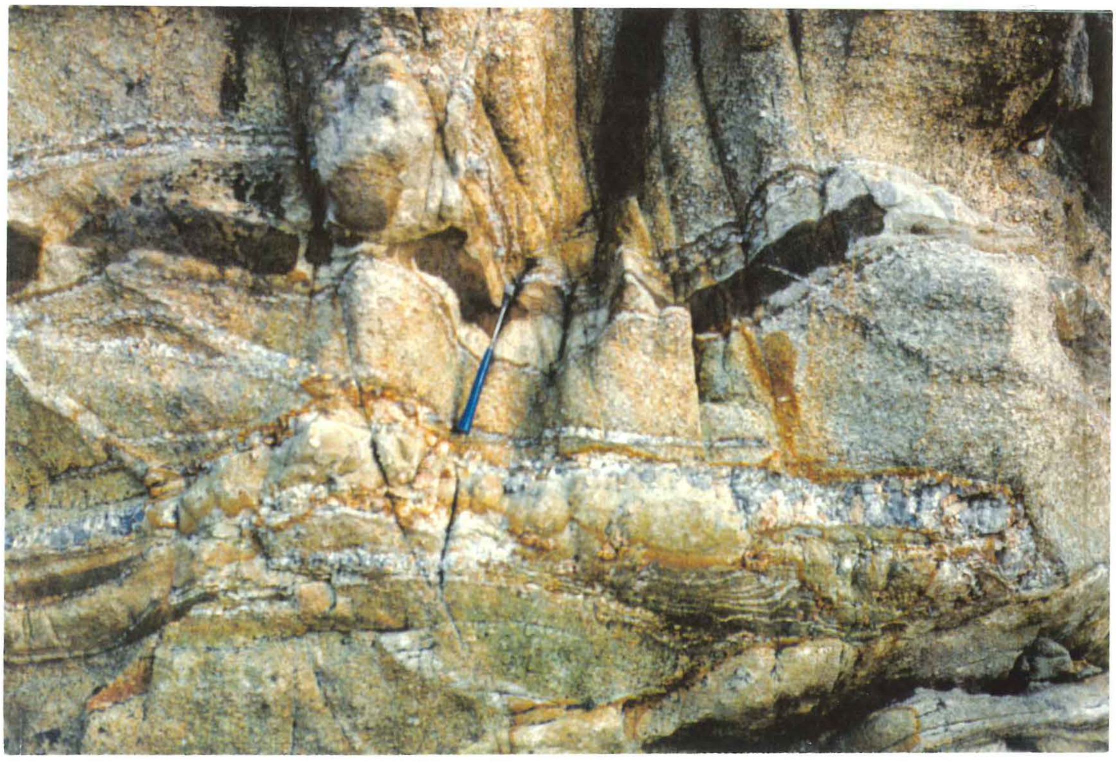


Figure 20: Complex relationships between fine-grained granite dikes, pegmatite dikes and mafic magma, south of Armchair Island.

Vernon, 1988). It is probable that both were only partially crystallised at the time of contact, and that each intruded the other - no evidence indicating a dominant direction of intrusion was found.

4.4: ENCLAVES

The debate over the genesis of enclaves within granitoids is at least as poorly resolved as the debate over pegmatite genesis. This is, in part, due to the greater variety of enclaves, and, by implication, due to there being a variety of ways in which enclaves may be generated (see Didier, 1973, for many of the older models; McBirney, 1979 and White et al, 1991 for some of the less common enclave varieties). However, the widespread occurrence of mafic microgranular enclaves (MME) in most granitoid intrusions has led to a refinement of the debate to concentrate on the genesis of this particular type. Although several hypotheses have been put forward, three have been identified as the most reasonable (Barbarin & Didier, 1991).

4.4.1: The Restite Model

One such hypothesis, supported by Chappell & White (1991), suggests that the enclaves represent unmelted residues entrained with the granite and brought up from the source area. These residues are termed 'restite', and are the refractory remnants of partial melting. As such, they are even more mafic than the original source material, having had the felsic granitic melt extracted from them. The occurrence of 'surmicaceous' enclaves, in particular, are commonly interpreted as restites from partial melting of sedimentary or supracrustal sources (eg Didier, 1973; Chappell et al, 1987). The interpretation of MME to fulfil a similar role, following the partial melting of an igneous or infracrustal source, is a direct extension of this hypothesis. The most convincing aspect of this model is the frequent absence of any evidence of an alternative mafic source for the enclaves, other than that from which the granite itself was derived; and the typically uniform and extensive distribution of MME throughout most granitoid bodies suggests they were sourced from some depth.

4.4.2: The Autolith Model

The mineralogical similarities between most MME and their hosts has led some to suggest that they are formed as 'autoliths' from the host magma (Barbarin & Didier, 1991). These autoliths are segregated from the melt, and accumulate to produce enclaves. This process, like the restite model, easily explains the uniform distribution of the enclaves, and requires no external sources. However, this hypothesis does not adequately explain the fine grain-size of the enclaves, as such segregations are more likely to be coarser than the host, rather than finer.

4.4.3: The Mixed Magma Model

The most widely favoured hypothesis is that the enclaves represent small, isolated bodies of mafic magma which have mingled with the host magma, without having become assimilated into it (Didier, 1973; Vernon, 1984, 1988; Barbarin & Didier, 1991). Many examples which show irregular contacts between mafic and felsic granites breaking up

Figure 21: Fine-grained granite intruding coarser granite, Armchair Island.

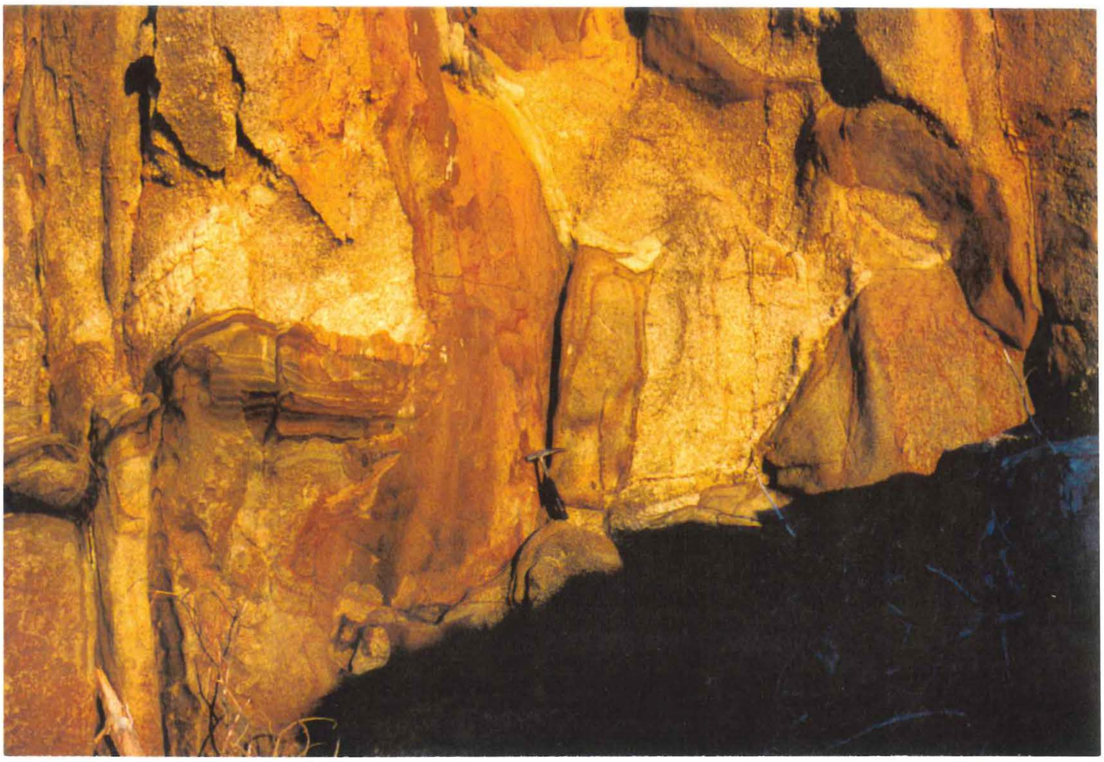


Figure 22: Complex contact relationships between fine-grained granite and megacrystic granite, south of Armchair Island.

to produce MME are known (eg Vernon, 1984; Wiebe, 1991; Pitcher, 1991), so there is little doubt that such processes do produce some MME. However, the extent to which these processes are responsible for all such enclaves, and the source of the mafic magma, are issues of debate.

4.4.4: Description of the Enclaves

Figure 23: Enclaves drawn out into elongate sheets. Locality of sample SP24 (Fig 34).

Throughout the Separation Point Batholith, small enclaves of fine-grained mafic material occur. These enclaves are typically spindle-shaped or elongate lenses, although larger enclaves may form sheets or screens (Fig 23 & 24). In contrast to the mafic material in more extensive areas of magma mixing, these enclaves rarely show evidence of significant hybridisation or assimilation with the surrounding granitic magma, their borders often being sharply defined by fine-grained selvedges.

Figure 24: Mafic microgranular enclave screen, east of Whariwharangi.

4.4.5: Discussion

The extreme elongation of some of the enclaves suggests that the enclaves were liquid during deformation. Vernon (1988) recorded aspect ratios of up to 40:1 for enclaves of gabbroic diorite in an undeformed tonalite, and pointed out that such extreme elongation is only likely to occur as a result of flow. Similarly, the high aspect ratios of many of the enclaves within the Separation Point Batholith can only have been formed while the enclaves were a liquid, and any such stretching can only be attributed to magmatic flow. The elongate nature also sheds doubt upon the possibility of the enclaves being derived from unmelted restite, or being accumulated segregations, as the microstructures (Chapter 6, Fig 34) are magmatic and show no sign of extreme deformation.

4.5: CONCLUSIONS

- Most of the Separation Point Batholith is remarkably homogeneous.
- The western boundary is marked by the mingling of a dioritic magma with the granite, producing hybrid compositions.
- An area of heterogeneity occurs along the east coast and probably represents the interaction of two comagmatic plutons.
- Fine-grained mafic enclaves are a common feature throughout the Separation Point Batholith.
- Many of the enclaves are elongated, sometimes to an extreme degree. This elongation and their magmatic textures, indicate they were subject to extension while they were liquid.
- The elongation of enclaves is a reliable indicator of direction of magmatic flow direction.

CHAPTER 5

STRUCTURAL ANALYSIS

5.1: INTRODUCTION

The Separation Point Batholith exhibits three pervasive structural features: joint sets, a foliation, and a lineation. These features have been used by many investigators to determine the structural state of a granitic body during emplacement and this chapter reviews some of their work. The structural features of the Separation Point Batholith are then described, and possible structural interpretations are discussed.

5.2: PREVIOUS WORK

5.2.1: Foliation, Lineation, and Joint Systems

The presence of pervasive structural features in granitoids has long been established, and precise descriptions of their interrelationships were first introduced by Balk (1937). The occurrence and distribution of planar and parallel linear features defined by alignment of such components as feldspar megacrysts, biotite flakes, amphibole needles or elongate enclaves, was identified and related to the shape of the batholith as a whole. Correlation of joint sets with foliation and lineation have also been established (Balk, 1937; Marre, 1986), leading to their subdivision into three systems: parallel joints, which have the same strike and dip as the foliation; cross joints, which are perpendicular to the foliation and lineation; and longitudinal joints, which are parallel to the lineation but perpendicular to the foliation. These systems have been found to be remarkably widespread, and their genesis has been related to the development of the fabrics themselves (Marre, 1986).

5.2.2: Structural Features as Indicators of Magmatic Flow

The early approaches to interpreting these features considered them to be related to magmatic flow during intrusion under passive tectonic conditions (eg Balk, 1937). Linear structures define the direction of flow during emplacement, while planar structures "represent a flattening against the slightly inclined and regular roof of plutons" (Marre, 1986). Under passive emplacement, the structures are defined by the shape of the walls and roof of the pluton, producing concentric patterns parallel to the pluton boundaries at a macroscopic scale (Balk, 1937; Marre, 1986; many other examples such as Lagarde et al, 1994).

5.2.3: Structural features as Indicators of the Tectonic Regime

However, further studies began to recognise the influence of tectonic stresses upon the primary structures, particularly where the macroscopic distribution was defined by these stresses rather than by the magmatic emplacement processes (Marre, 1986; McCaffrey, 1992). These studies contrasted their distributions with those of passive intrusions to extract information on the stress system and tectonic regime at the time of emplacement (eg Hutton et al, 1990; Karlstrom et al, 1993).

5.3: DATA COLLECTION AND EVALUATION

Over the six trips to the field area, a large body of data was collected in the form of strike & dip or trend & plunge values describing the distribution of the foliation, lineation and joint systems. Primary jointing provided the largest data set, as most localities had multiple joint sets visible. These sets were not recorded separately , but proved to be consistent enough to appear as separate sets after data analysis. Foliation and lineation, where visible, were also measured. The strength of these fabrics is somewhat variable, but over most of the field area it is weak but measurable. The orientation of the fabric in the granite appeared to vary considerably over short distances, but, overall, remains remarkably consistent. Particular attention was paid to looking for shear sense indicators associated with the formation of the granitic fabric, such as S-C fabric, asymmetric megacrysts or strain shadows. However, none of these structures were observed, even in the highly strained granitoids at Tata Beach

The structural data collected in the field was plotted up on a Schmidt equal-area net, and contoured using a spherical Gaussian weighting function. After the first set of data was acquired, some plots were made separating data by area, but these plots did not produce unique patterns. All future data was simply added to the combined data set, and was found to simply reinforce the patterns already present - just by comparing each combined set with the previous set, it was apparent that there was no significant variation of the structural trends over the area investigated

5.4: DESCRIPTION OF STRUCTURAL FEATURES

5.4.1: Foliation

Throughout most of the Separation Point Batholith, the granite exhibits a planar fabric defined by the parallel alignment of planar minerals, most notably biotite. Due to the low percentages of biotite in some parts of the batholith, and the fine grain-size typical of the biotite, this fabric is often very difficult to distinguish. Planar shaped enclaves occasionally occur and these help to define the foliation, especially those that form screens of mafic minerals aligned with the fabric. Although the planar fabric probably also implies the presence of a linear preferred orientation of minerals, such as feldspar and quartz, this alignment is not recognisable in the field. The foliation data are shown plotted on an equal area net in Fig 25, and are discussed below.

5.4.2: Lineation

A linear fabric is also common throughout the batholith, although it is often quite difficult to recognise. It is defined by the parallel alignment of quartz rods and prismatic feldspar grains, particularly potassium feldspar megacrysts. Because these minerals do not have high aspect ratios and prefer to form a simple interlocking aggregate, the lineation is only apparent when it is strong enough to overcome the normally massive granitic texture, or where the more independent prismatic megacrysts are common enough to define the fabric. Alignment of planar biotite flakes around a common axis also occurs in association with the alignment of the felsic minerals, and enclaves drawn out into spindle or lens shaped bodies help define the lineation in places. The

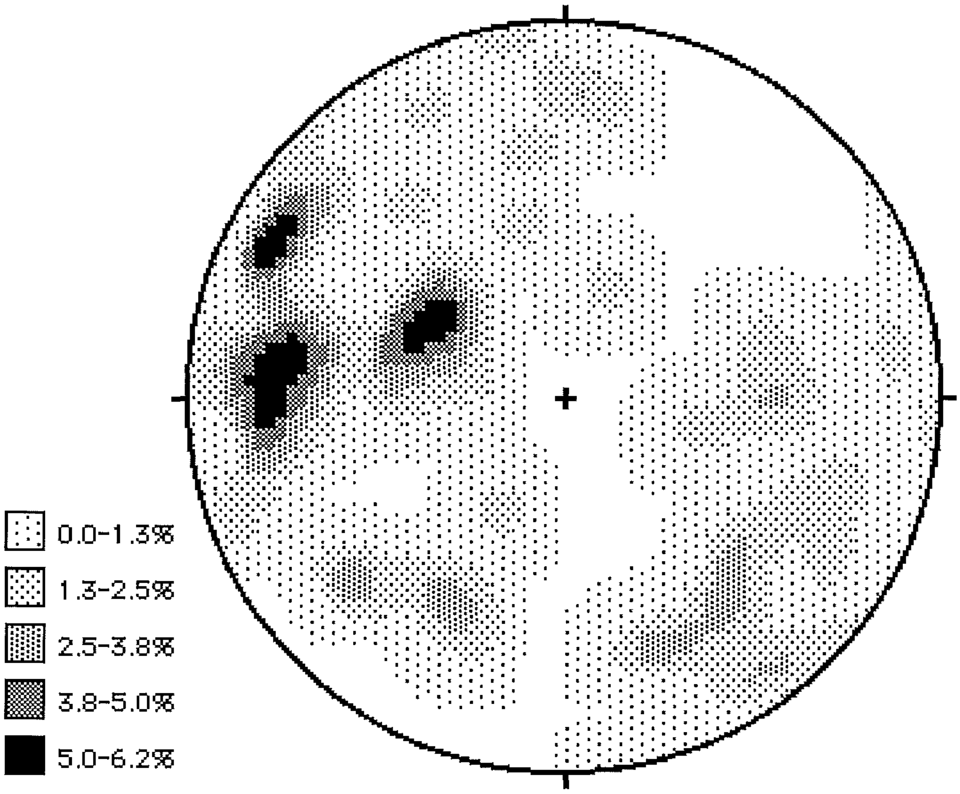


Fig25: Poles to foliation. N = 55.

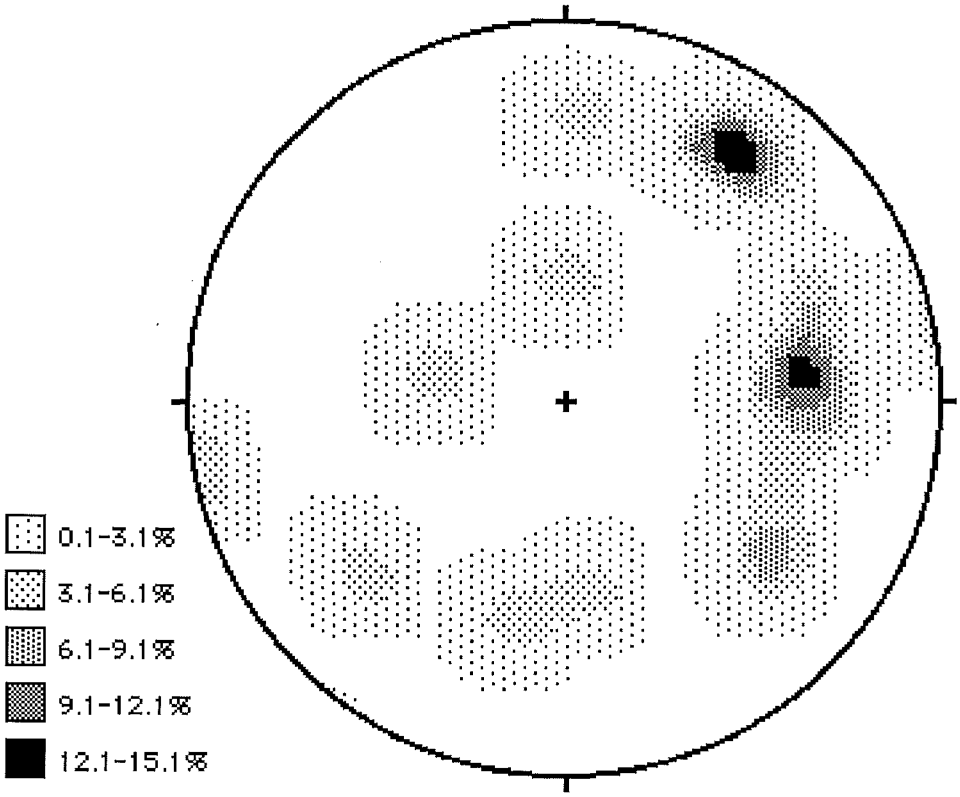


Fig26: Lineations. N = 19.

lineation data are shown plotted on an equal area net in Fig 26, and are discussed below.

5.4.3: Jointing

Joints are the most common and consistent structural features throughout the Separation Point Batholith. They typically develop as three mutually perpendicular sets, and, although the strength of development may vary, all three are usually visible at any location where jointing is apparent. Plotting of the jointing data taken in the field clearly identifies the presence of the three common joint sets.

The most recognisable set in the field is the horizontal or sub-horizontal set, although this set was often difficult to identify on the shore platforms, being more apparent in the cliffs behind. The other two sub-vertical sets are shown on the stereo plots to also have remarkably consistent attitudes, although this was less apparent in the field due to local variation. One set strikes East-South-East / West-North-West while the other strikes approximately North / South. Although one of these sub-vertical sets may be difficult to identify locally in a parallel cliff face, it was normally visible on the shore platform or in nearby prominences. The jointing data are shown plotted on an equal area net in Fig 27, and are discussed below.

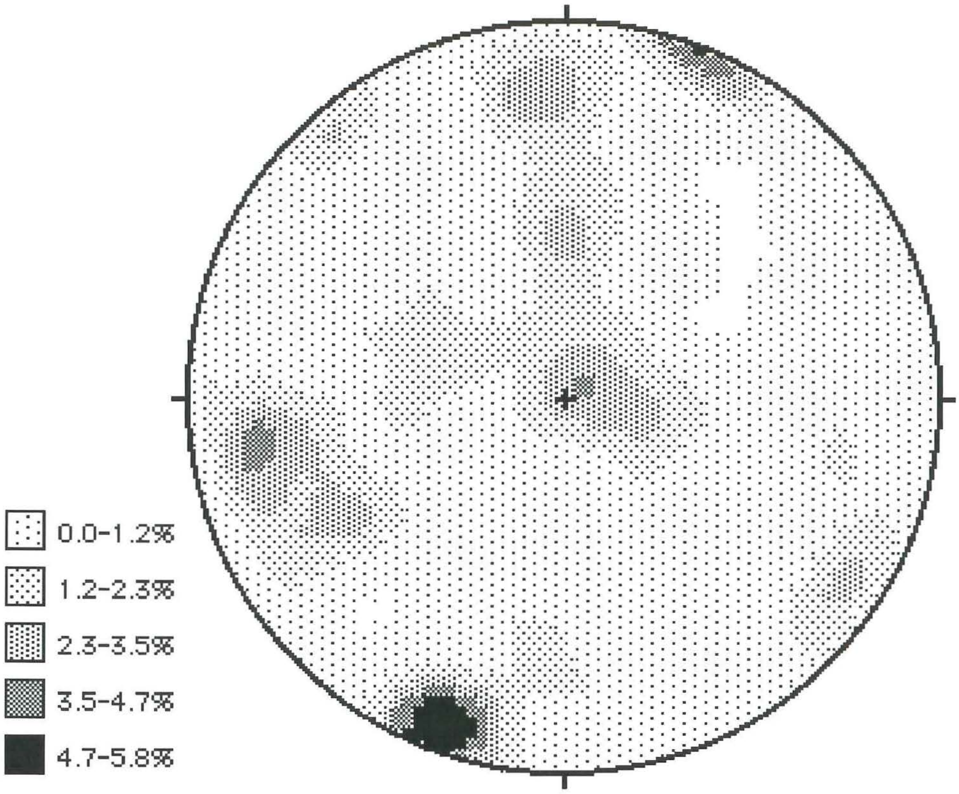


Fig 27: Poles to Jointing Planes. N=168

Fig 28: Strong foliation and lineation developed oblique to flow direction as defined by elongate enclave.

5.5: DISCUSSION OF STRUCTURAL FEATURES

5.5.1: Primary Flow versus Later Deformation

Although it is often initially assumed that granitic fabrics are simply the result of magmatic flow, with the fabric developing in response to differential flow during passive emplacement, this is not always the case. The flow itself is often strongly influenced by the regional stress state, and, as the body crystallises, these regional stresses may become more directly influential.

In the Separation Point Batholith, fabric developed as a result of primary magmatic flow is best indicated by the association of parallel, elongated enclaves, as the elongation of the enclaves themselves is considered to be in response to this flow. This frequently coincides with the local foliation and lineation, but there are examples in the Separation Point Batholith where the dominant fabric is clearly oblique to the elongation of the enclaves present (Fig 28). This would suggest that in some cases the fabric was formed as a later tectonic overprint after the magma had mostly solidified, so that the enclaves were not realigned in response to the stresses applied.

5.5.2: Discussion of Structural Data

The stereographic plots of the lineation and foliation data both show strong trends. The foliation typically dips steeply to moderately to the east or south-east, while the lineation plunges at a more gentle angle to the east or north-east. The oblique angle of the lineation relative to the foliation suggests that the regional stresses were similarly oblique, their orientation indicating either a thrusting movement from the east with dextral strike-slip, or a reverse extension with sinistral strike-slip. However, the lack of shear sense indicators severely limits the interpretation of these structures, making it difficult to determine which of these is correct. It is hoped that reference to tectonic models will help to constrain the structural regime and define the movement direction.

Although there is a lot of scatter, the trends are remarkably strong, and are a lot more consistent than they appeared to be in the field due to local variations. The strength of the trends is also surprising given that the data could not be divided into sets according to whether the fabric was formed by primary magmatic flow or later deformation. The presence of both can be attested to from field relationships, but the fact that the resulting trends are so consistent suggest that the primary magmatic flow was strongly influenced by the regional stress regime, and that, when flow ceased and solid-state deformation set in, the resulting deformation remained consistent with the earlier structures.

The jointing data clearly show three systems of approximately perpendicular sets. Furthermore, these systems are so oriented with respect to the average lineation that they approach the pattern expected for the three standard joint systems: one sub-horizontal set and one sub-vertical set parallel to the lineation, and one set perpendicular to the lineation. However, this relationship was not observed consistently in the field, and was only apparent once the structural data was plotted up. The lack of visible correlation in the field is probably due to the fact that most of the granitic fabric is no longer primary flow fabric, but is formed through later deformation. Locally, this fabric does not precisely match the attitude of the primary flow fabric and its associated jointing patterns, but, because both fabrics were influenced by regional stress patterns, the overall correlation, as seen in the stereo plots, is consistent with the expected pattern.

5.6: COASTAL EXPOSURE OF THE WAINUI SHEAR ZONE

5.6.1: Description

The headland at the western end of Tata Beach, exposing the north-western margin of the Separation Point Batholith, appears to be the northern end of the Wainui Shear Zone. The mixed dioritic to granitic rocks are highly strained, with a strongly developed foliation dipping steeply to the east with a down-dip lineation.

The foliation is defined in the dioritic rocks by the alignment of fine-grained biotite and hornblende and also by the deformation of purer dioritic enclaves within hybrid rocks. These enclaves are drawn out into long lenses extended parallel to the foliation, and are often the most obvious expression of the fabric. In the granitic rocks, the fabric is defined by quartz ribbons, visible as streaks, elongated in the direction of the lineation. These rocks are distinctive due to their low mafic content and strong structure, producing pale, strongly jointed outcrops with a wooden appearance.

5.6.2: Discussion

The most striking aspect of the Tata Beach exposure is the inconsistent development of the strain between the different rocks outcropping there. In the dominant granitic rocks, the strain is strongly developed, always maintaining the same attitude and orientation. This consistency is maintained even where the granitic rocks form isolated masses surrounded by dioritic and hybrid rocks. In contrast, the minority dioritic rocks display a weaker fabric with attitudes which can vary substantially. The fabric is often deflected around local obstructions such as enclaves or neighbouring granitic domains. This variable and inconsistent fabric is also developed in all but the most felsic of the hybrid rocks.

The development of this inconsistent fabric is probably a result of the partitioning of the strain between the different domains, which favours the felsic granitic rocks over the more mafic dioritic rocks. The reason for this partitioning is the relative abundance of quartz in the granitic rocks, allowing them to deform more easily in response to the regional stress patterns. In contrast, the dioritic rocks have deformed only after their resistance has produced more concentrated stress fields around them, the highly variable nature of their deformation being a result of the irregular and inconsistent orientation of these local stress concentrations.

5.7: CONCLUSIONS

- There are three pervasive structures present throughout the Separation Point Batholith: a foliation, a lineation, and jointing.

- The foliation dips moderately or steeply to the east, and the lineation plunges gently to the north-east.
- This orientation suggests that emplacement occurred either under east-over-west thrusting and dextral strike-slip, or top-to-the-east extension with sinistral strike-slip.
- Three jointing systems are present, approximately oriented as cross joints, parallel joints, and longitudinal joints.
- Foliation and lineation do not always represent the primary magmatic flow as indicated by the more reliable elongate enclaves.
- The remarkably consistent orientation of the foliation, lineation and jointing data, despite locally conflicting field relationships, indicate that both primary magmatic and later deformational features were strongly influenced by consistent regional stresses.
- The western margin of the batholith is highly strained, with a foliation dipping steeply to the east and a strong down-dip lineation.
- The distribution of this intense strain is uneven, with strain being partitioned into the more easily deformed granitic rocks.

CHAPTER 6

MICROSCOPIC STUDIES

6.1: INTRODUCTION

Microscopic studies of the Separation Point Batholith were carried out for two reasons: firstly, to assist in petrological investigations, particularly in respect to determining modal compositions; secondly, to determine the microstructures present, and to relate these structures to the larger-scale structural setting. This chapter describes the methods and results of these studies. As part of the structural investigation, oriented thin sections were investigated using the universal stage, and a discussion of previous work using this method and the results from this study are also discussed below.

6.2: METHODOLOGY

6.2.1: Sample Collection

Samples were collected for two purposes. During reconnaissance they were collected for microscopic identification of mineralogy, so were simply labelled and their location recorded. During the later trips, however, they were collected to provide additional structural information, such as identifying the nature of the granitic fabric, or attempting to identify shear sense. These samples had their orientation marked on them and recorded so that any structural information derived from them could be related back to their field position.

6.2.2: Sample Preparation

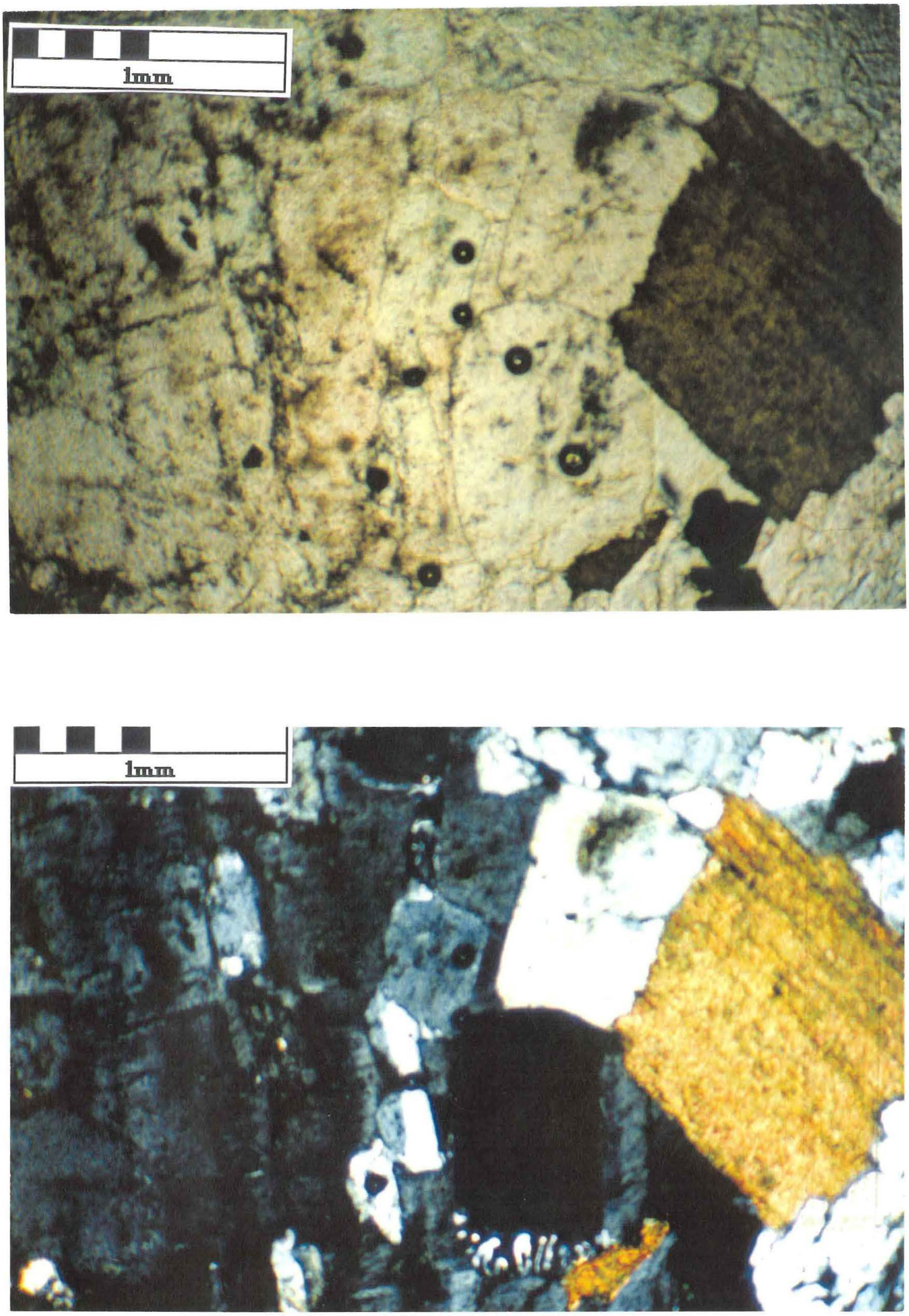
Samples taken during reconnaissance had thin sections cut from them so that their composition could be determined accurately. These sections were cut perpendicular to any fabric present so that the greatest variety of minerals would be visible. The oriented samples taken later, however, were cut parallel to lineation and perpendicular to foliation so that any shear sense indicators associated with these structures could be identified. These sections were also marked so that the orientation of the structural data derived from them could be related back to their field position.

6.2.3: Flat Stage

All of the samples were viewed on the flat stage, using standard techniques, for mineral identification. Approximate modal compositions were determined for the purpose of petrological classification of the samples. The presence of microstructures was also noted, particular attention being paid to look for shear sense indicators such as C-S planes, mica 'fish', asymmetric fracturing or rounding of phenocrysts, and rotated strain shadows.

6.2.4: U-Stage

Oriented sections from the highly strained rocks at Tata Beach were investigated using U-Stage techniques. These investigations were carried out to determine the shear sense of the strain applied to these rocks after it was found that no other shear sense indicators could be seen. Measurements of the orientation of the quartz c-axes relative to the



<u>Figure 29:</u> Photomicrograph of sample SP45. Typical granite, with poikilitic alkali feldspar (left), quartz, plagioclase, biotite and myrmekite.

orientation of the lineation and foliation were made, and plotted on Schmidt equal-area nets. These plots should show an asymmetry about the fabric orientation which can be used to determine the shear sense of the strain applied to the quartz (see discussion below, 6.5.1). Measurements were taken only from those quartz grains that formed part of the quartz ribbons, as this would avoid those grains less affected by the deformation.

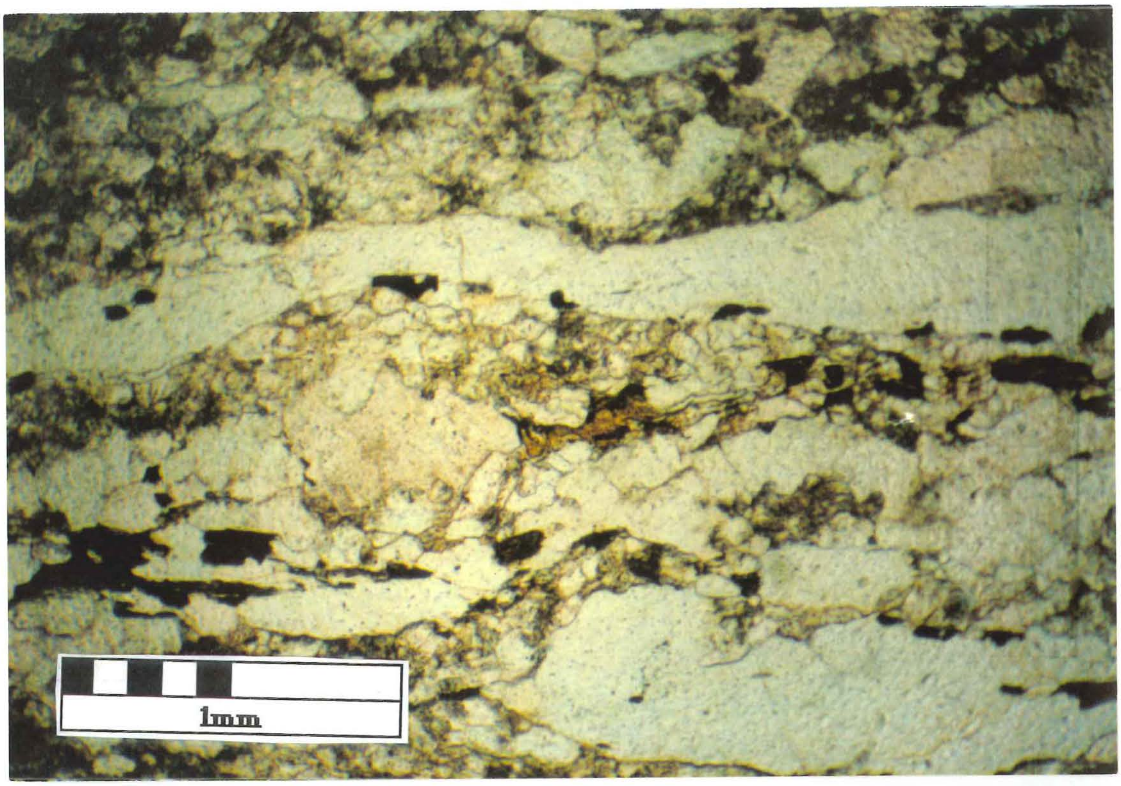
6.3: MINERALOGY AND PETROLOGY

6.3.1: Eastern Separation Point Batholith

Along the eastern coastline of the Abel Tasman National Park, the mineralogy and petrology of the Separation Point Batholith is remarkably uniform. Although areas occur where magma mixing or concentrations of alkali feldspar megacrysts are significant enough to change the composition of the local rock, the majority is notably consistent. Quartz, alkali feldspar and plagioclase are present in approximately equal quantities in all samples taken from this area, the rock being classified as a monzogranite (according to the nomenclature of Le Maitre, 1989). Biotite and opaques are also always present in small quantities, typically around 5%, but never exceeding 10%. Accessory minerals include titanite, muscovite and zircon (Fig 29).

6.3.2: Separation Point to Tata Beach

From Separation Point, the composition of the batholith changes westward, becoming more intermediate. Hornblende appears and plagioclase becomes more dominant until, west of Whariwharangi, the



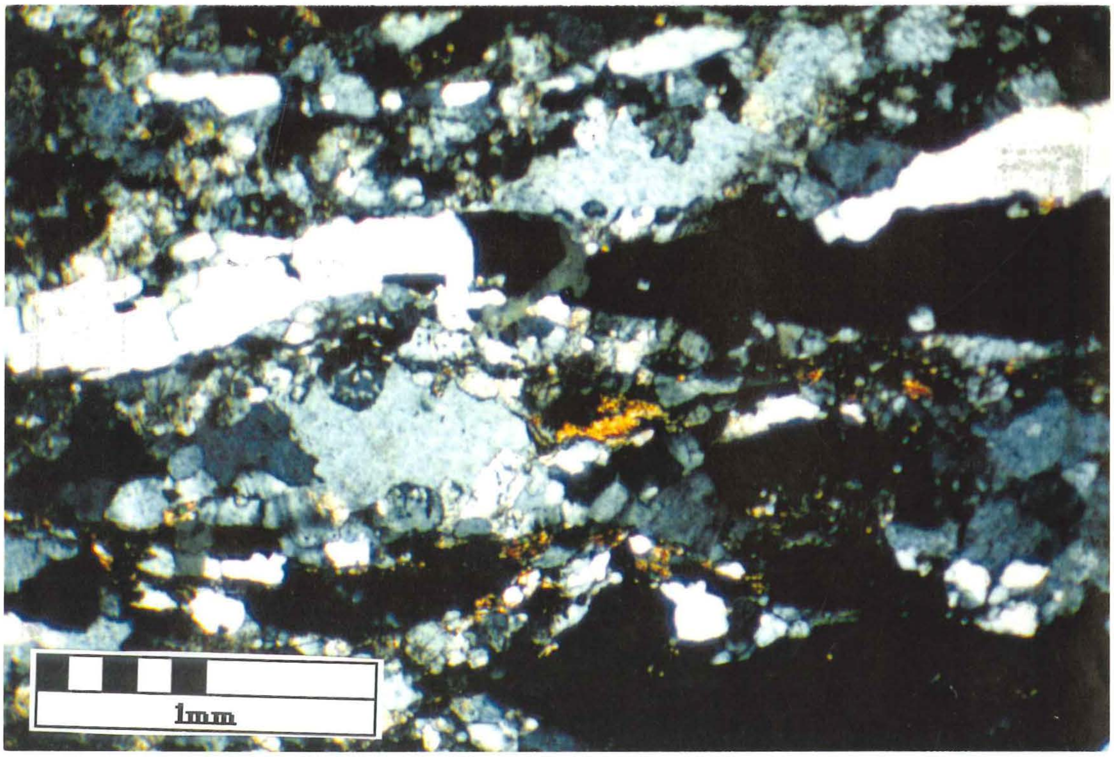


Figure 30: Photomicrograph of sample SP36. Highly strained granite from Tata Beach, with extremely elongate quartz ribbons in a fine-grained matrix of quartz, alkali feldspar, plagioclase and biotite. Myrmekite (left of centre) is also common. Quartz c-axes plotted in Fig 37 & 38.

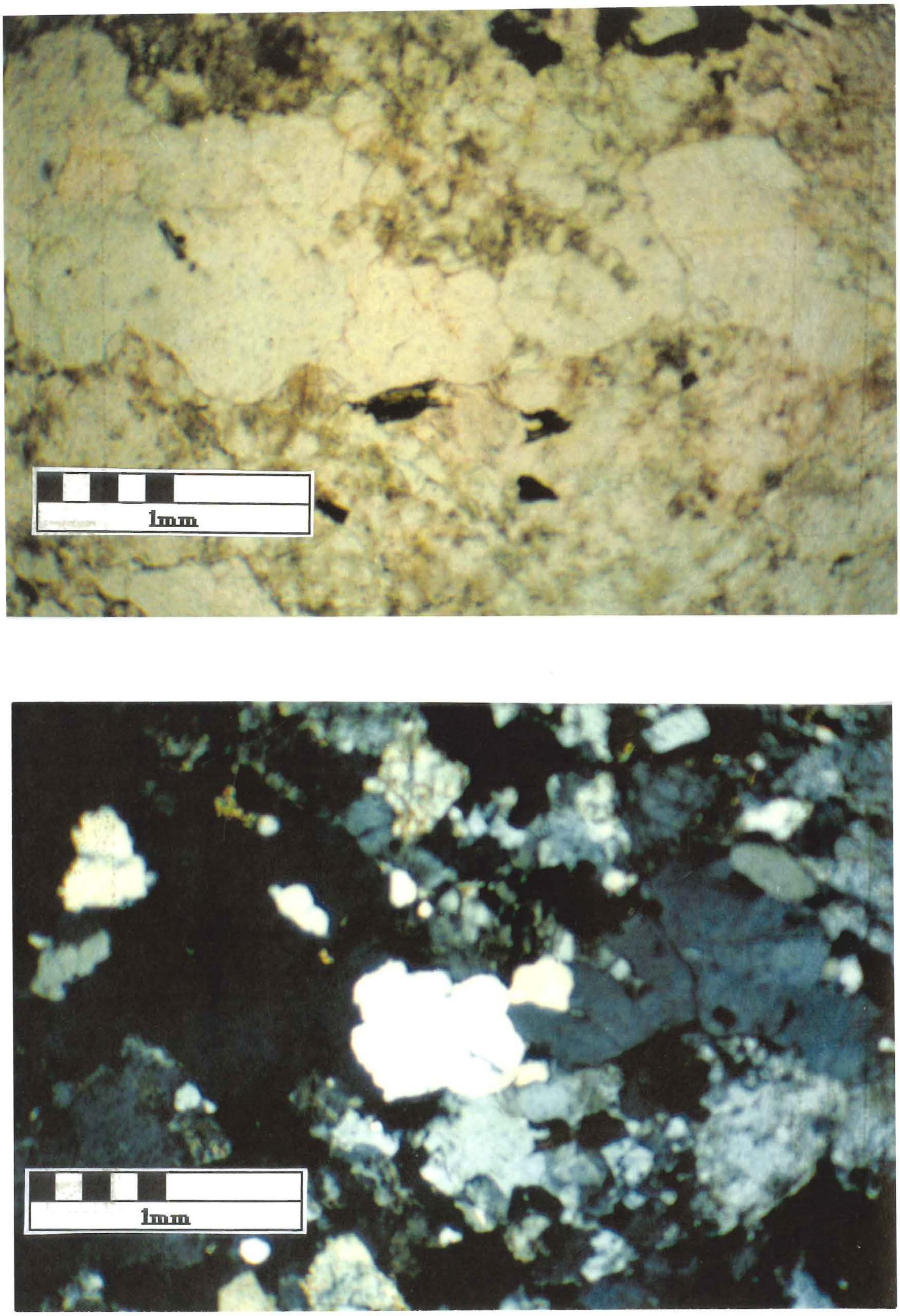


Figure 31: Photomicrograph of sample SP40. Strained granodiorite with coarser quartz ribbons than SP36 (Fig 30). Matrix grain size is still fine. Quartz c-axes plotted in Fig 39.

rock grades into a granodiorite. However, the proportion of mafic minerals does not increase significantly, with hornblende never exceeding 2%. Accessory garnet also appears along the northern coastline.

6.3.3: Tata Beach

The rocks outcropping on the coast of the headland at the western end of Tata Beach are of hybrid composition. They range from felsic syenogranites rich in quartz (> 50% in some samples, Fig 30) and free of hornblende, through hornblende-bearing monzogranites and granodiorites (Fig 31 & 32), to diorites with 25% mafic minerals, no alkali feldspar and only interstitial quartz (Fig 33).

6.3.4: Enclaves

Samples of enclaves show these fine-grained mafic bodies to be micro-diorites or quartz micro-diorites. Although rich in mafics (>50%), those along the east coast are free of hornblende, consisting almost entirely of biotite, plagioclase and opaques (Fig 34). The fine-grained mafic dikes at Tata Beach, which appear to be similar to the enclaves in the hybrid rocks, have only 20% mafic minerals, 2% of which is hornblende. Quartz also occurs in moderate proportions (15%), the remainder being plagioclase (Fig 35). Alkali feldspar was not observed in any of the enclave samples.

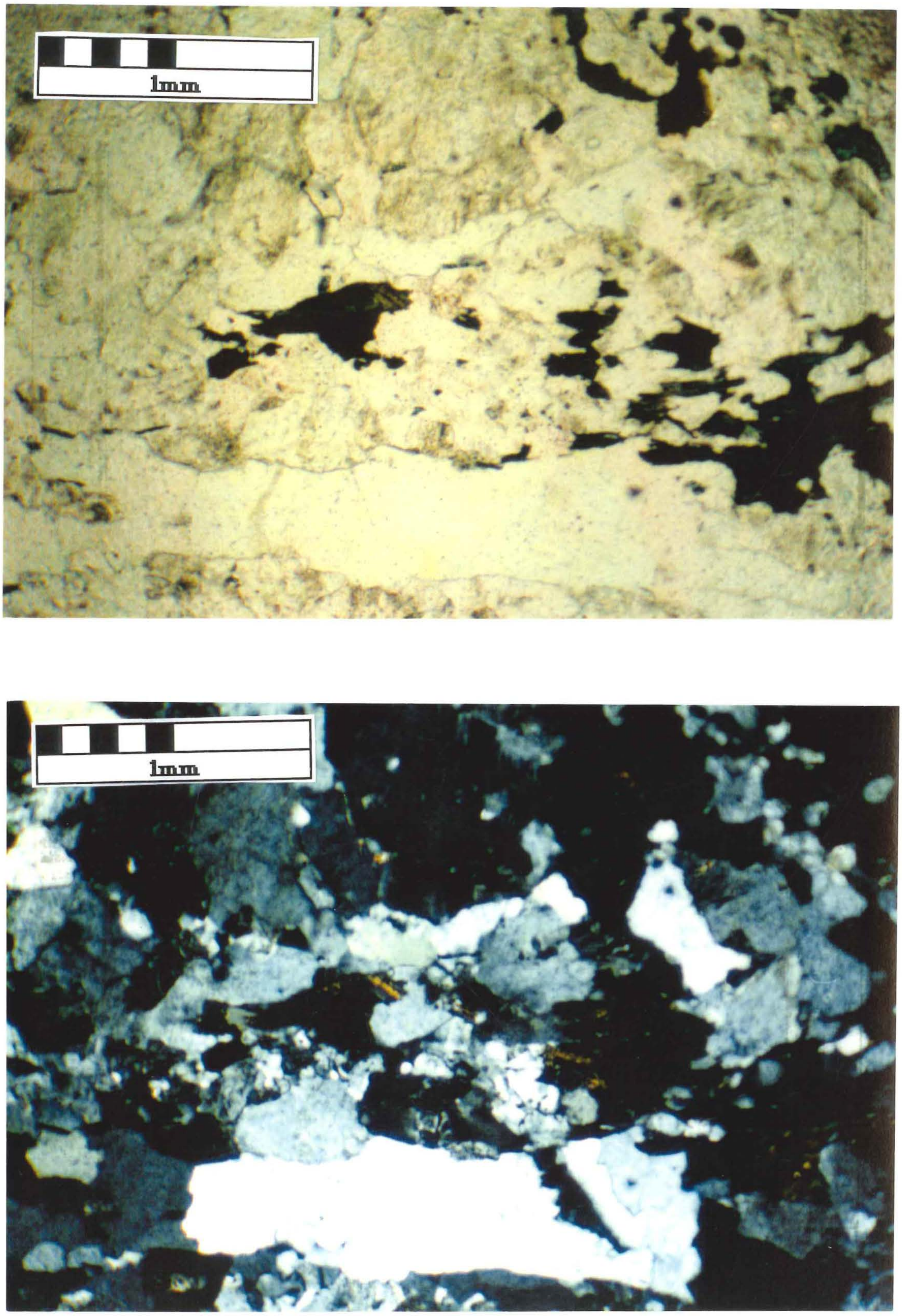


Figure 32: Photomicrograph of sample SP5c. Strained hornblende granodiorite. Quartz is sparser, often forming lakes instead of ribbons. Matrix grain size is coarser. Quartz c-axes plotted in Fig 40.

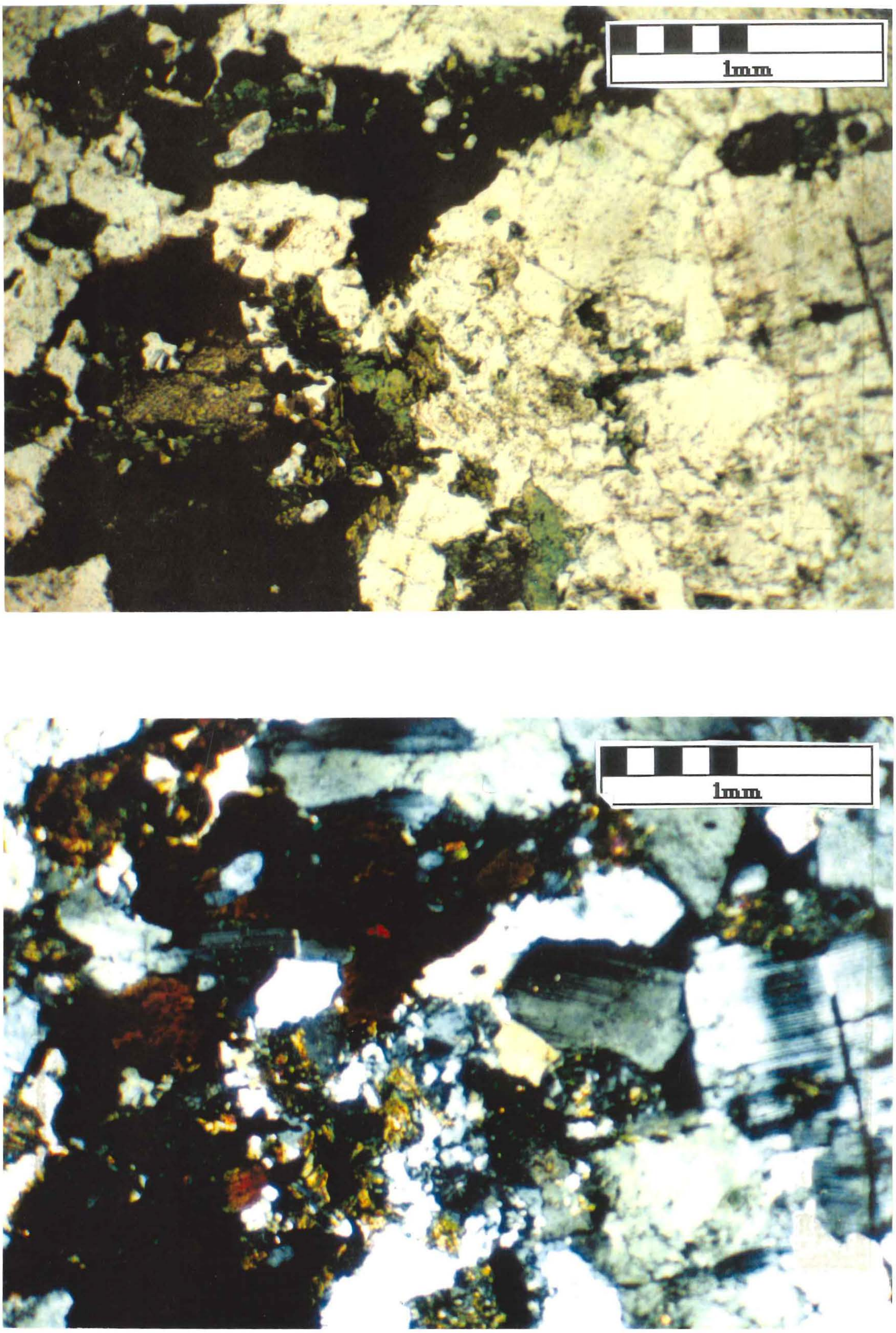


Figure 33: Photomicrograph of sample SP37. Relatively unstrained diorite from Tata Beach (Fig 16). Mostly plagioclase, with brown biotite, green hornblende and interstitial quartz.

6.4: MICROSTRUCTURES

6.4.1: Typical Granitic Textures

Throughout most of the Separation Point Batholith, the rocks display typical granitic textures. Plagioclase, biotite and hornblende is typically euhedral, with subhedral alkali feldspar and anhedral, interstitial quartz. Along the eastern coastline, alkali feldspar is more dominant, forming large (up to 5 cm) phenocrysts and poikilitically enclosing other minerals (Fig 29).

Both plagioclase and alkali feldspars are commonly zoned and twinned. Twinning includes primary Carlsbad twins and deformation albite twinning in plagioclase and transformation (cross-hatched) twinning in microcline. Myrmekite is also common throughout the batholith. The linear and planar fabrics visible in the field are at best recognisable in thin section as a weak preferred orientation of plagioclase laths or of scattered mafic minerals. No evidence was found to indicate the sense of shear applied to develop the fabrics.

6.4.2: Tata Beach

The highly strained rocks outcropping at the western end of Tata Beach display quite different textures from the rest of the Batholith. The strong fabric is clearly visible in the field and in thin section, being especially well defined by the alignment of trains of mafic minerals. The grain size of all minerals is considerably reduced, with the exception of the polycrystalline quartz ribbons, and grains are anhedral with serrated boundaries (Fig 30 - 32). These effects are less developed in the more

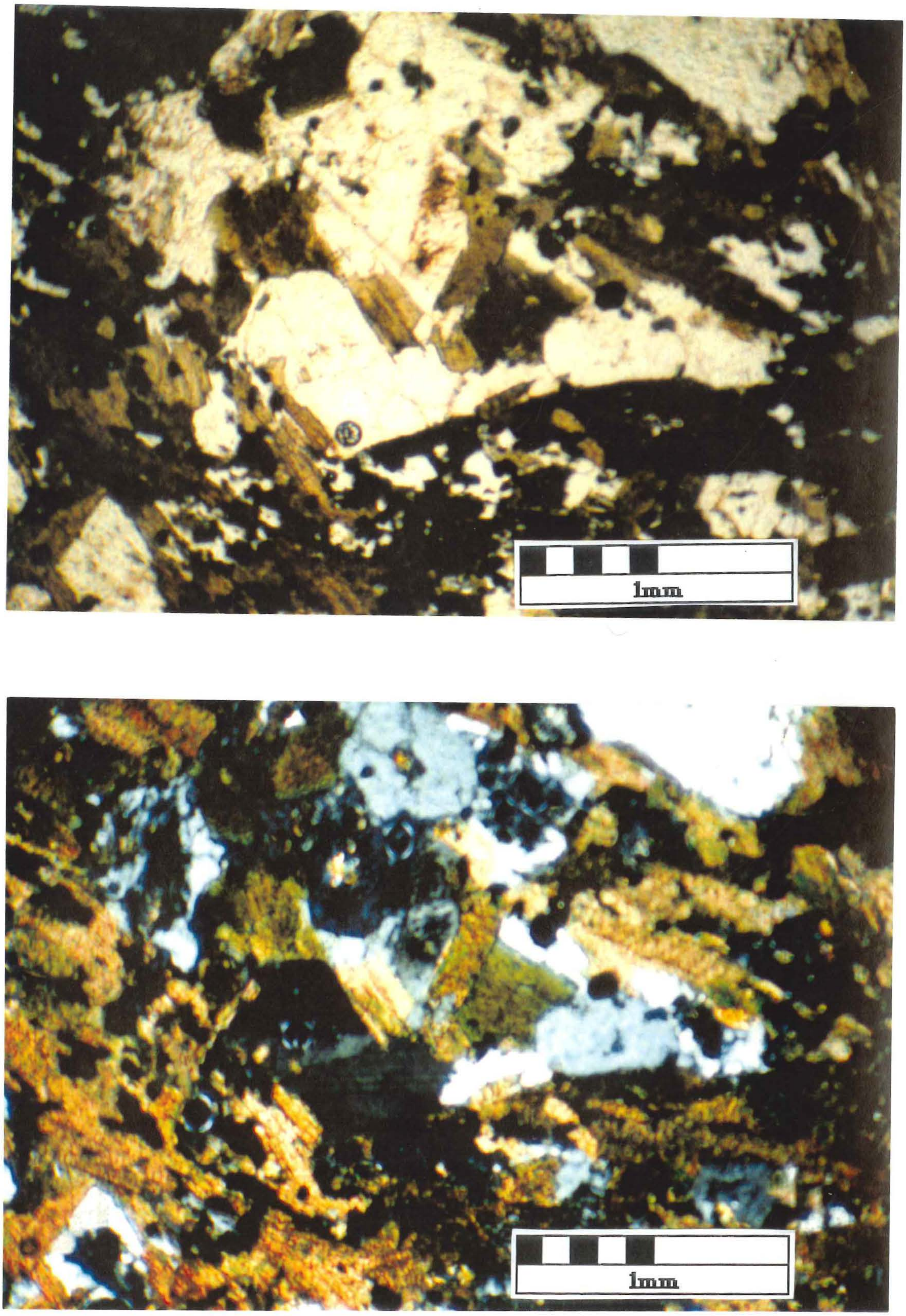


Figure 34: Photomicrograph of sample SP24. Enclave from south of Totaranui (Fig 23), consisting almost entirely of plagioclase and biotite.

mafic hybrid or dioritic rocks (Fig 33), suggesting that the strain has been concentrated in the quartz-rich felsic rocks.

Quartz ribbons are a particularly dominant feature of these granitic rocks, being several millimetres long and around 0.2 mm thick in the most strained (Fig 30). The ribbons are less drawn out in those rocks which are poor in quartz, typically forming elongate lakes in the hybrid rocks (Fig 32). Occasional large relic grains of plagioclase or alkali feldspar occur, with their crystal boundaries rounded and the fabric deflected around them. Despite the strength of the fabric and careful investigation, no indication of the sense of shear applied to these rocks was recognised. Even the feldspar relics gave no indication of rotation, and no C-S planes were visible.

6.5: U-STAGE

6.5.1: Introduction

The use of the universal stage for determining the crystallographic orientation of minerals has proven to be particularly applicable to fabric studies. Quartz c-axis data, in particular, have been used to determine such information as extension directions, strain symmetry, strain paths and the active crystallographic slip systems (see Law, 1990, for an excellent review). Perhaps the most common application for such studies is to determine a sense of shear in plastically deformed rocks. This can be determined by relating the orientation of the lineation and foliation (finite strain features) to the distribution produced by the quartz c-axes (Lister & Hobbs, 1980; Etchecopar & Vasseur, 1987). It has been

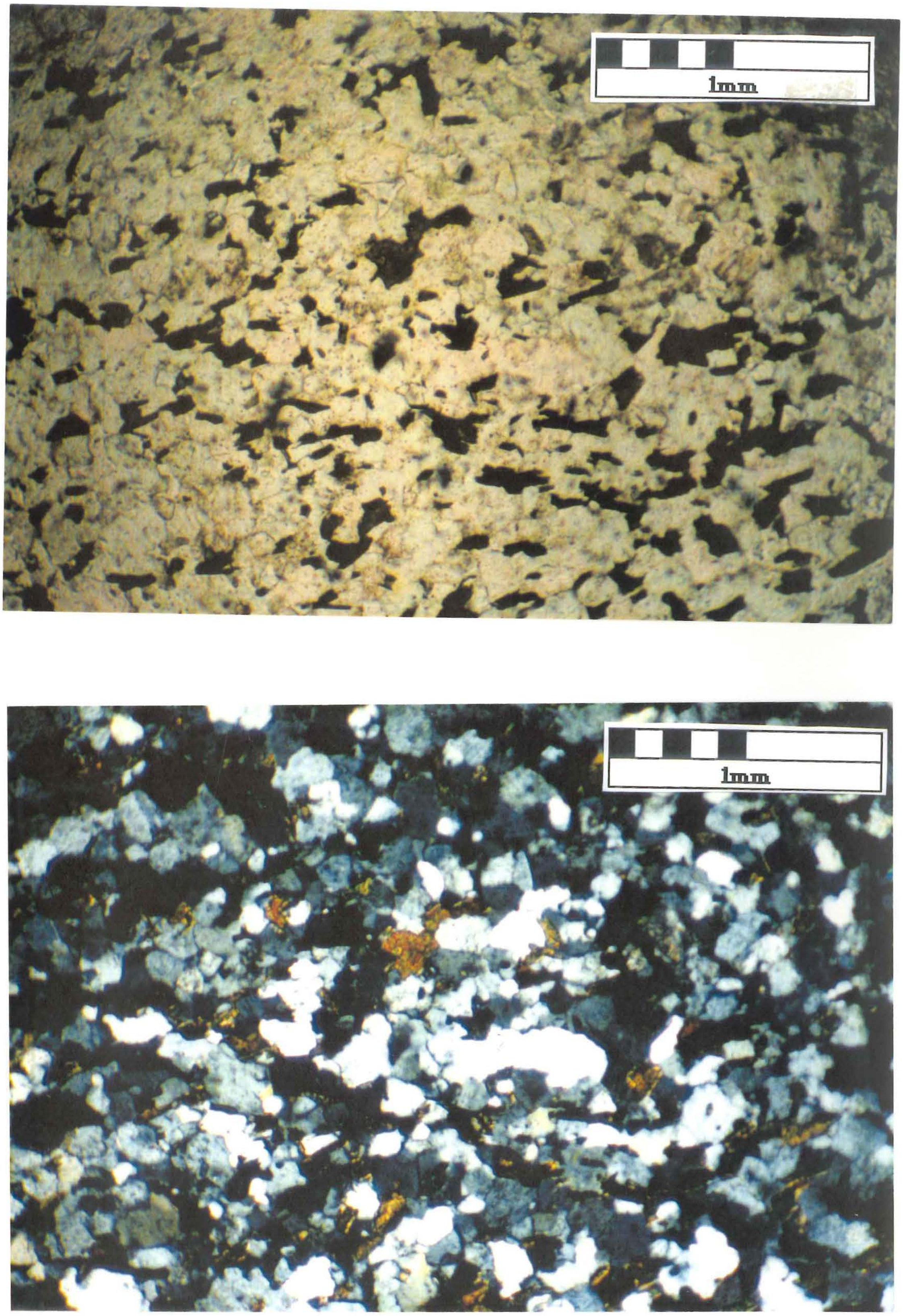


Figure 35: Photomicrograph of sample SP6c. Fine-grained mafic dike from Tata Beach (Fig 18). Flow foliation visible as alignment of mafic minerals, mostly biotite.

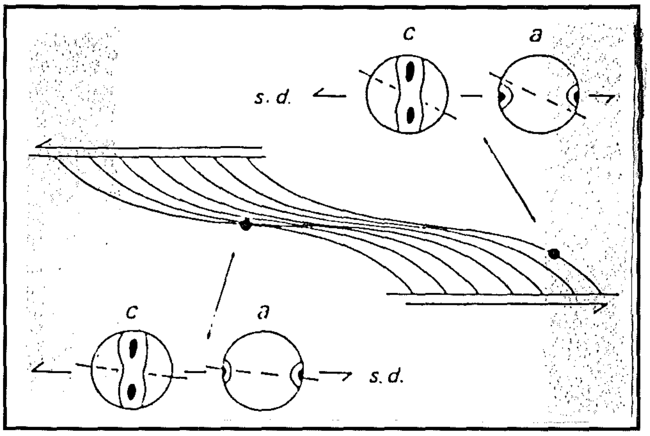


Figure 36: Schematic illustration of foliation pattern in an idealised zone of heterogeneous simple shear and angular relationships with increasing shear strain between finite strain features (foliation and lineation) and quartz c and a-axis fabrics; all relationships shown on XZ section plane of finite strain ellipsoid; s.d., shear direction. From Law (1990, Fig 3).

found that, under the most common slip system (basal <a> slip), the c-axis distribution develops a girdle perpendicular to the shear direction, so that a comparison of this distribution with the finite strain features will give an indication of the sense of shear (Fig 36).

6.5.2: U-Stage Results from Tata Beach

The orientation of the c-axes of 300 quartz grains were determined for each sample, and were found to produce one or two concentrations which are contained within a plane perpendicular to the foliation and parallel to the lineation (Fig 37 - 40). These concentrations are close to the orientation of the lineation (within 20 to 35°), and a weak girdle links the point concentrations. Where two concentrations are present, they are approximately symmetrical about the lineation, though the strengths of concentration are often different.

6.5.3: Discussion

These results are unusual and do not match the common patterns as described in the literature (eg Law, 1990, and references therein).

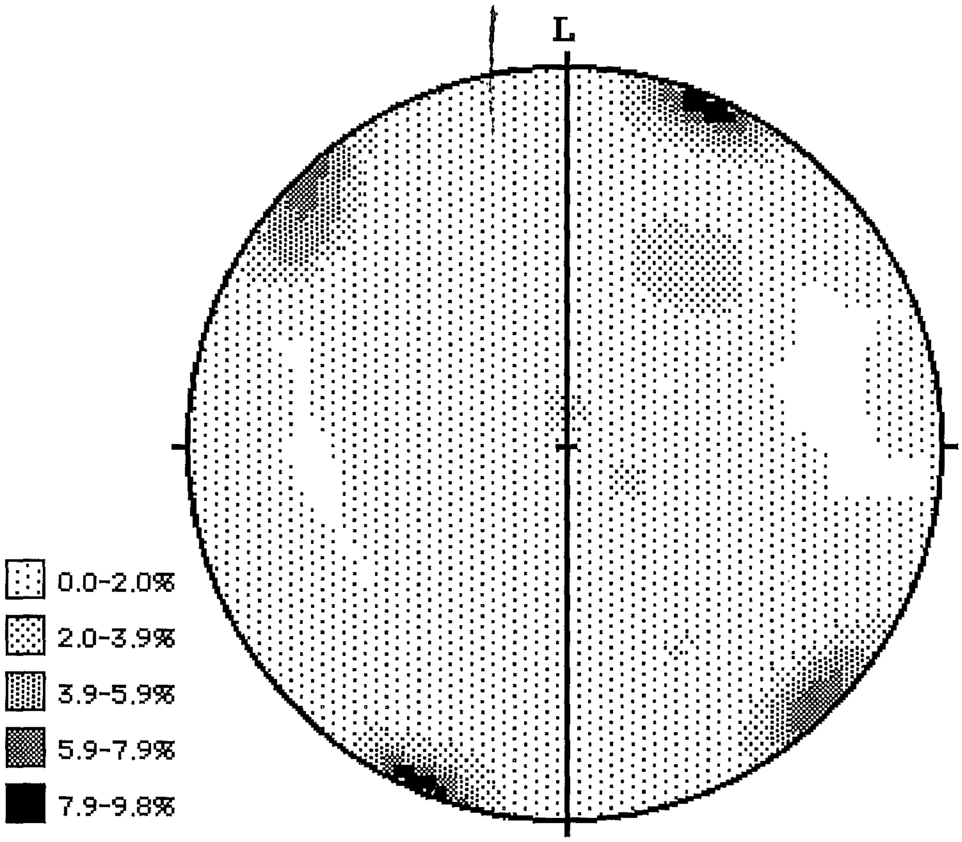


Fig37: Sample SP36 quartz c-axes. See Fig30. N=305.

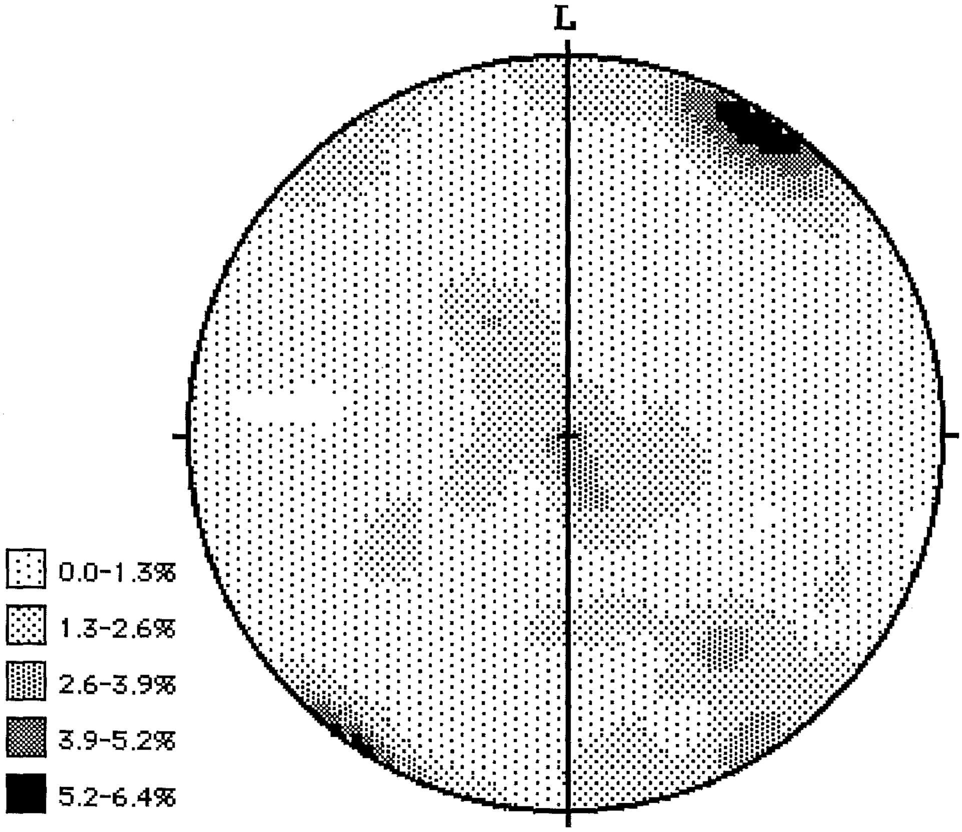


Fig38: Sample SP36a quartz c-axes.
Cut from the same sample as SP36 above. N=304.

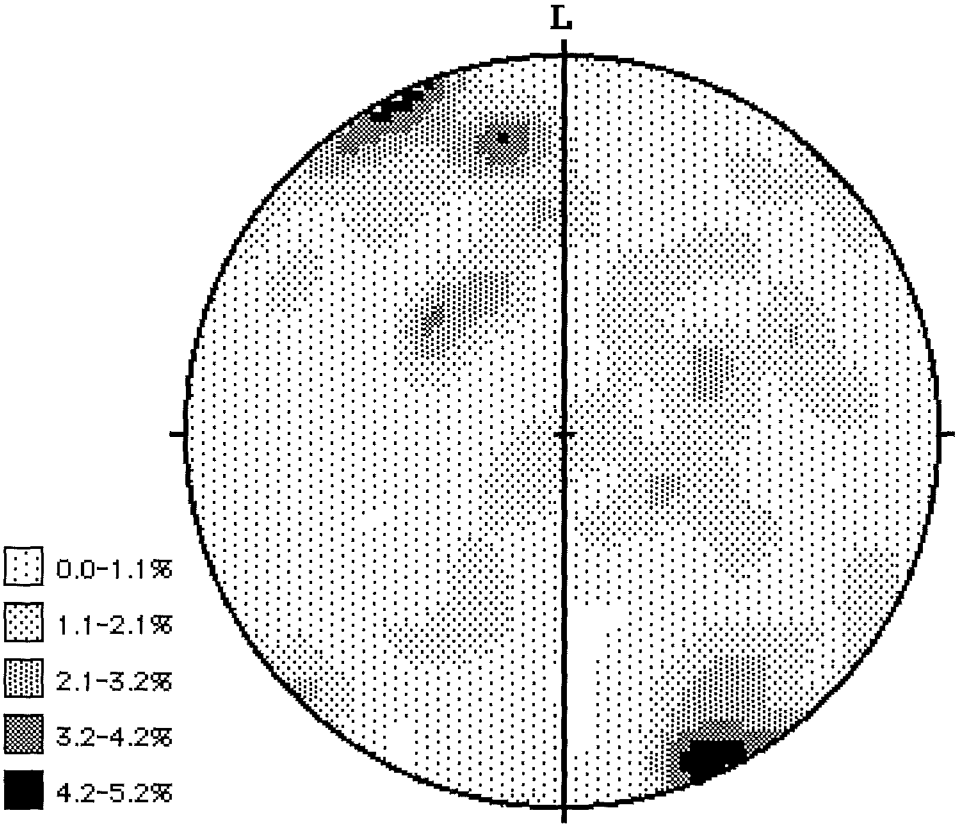


Fig40: Sample SP5c quartz c-axes. See Fig32. N=176.

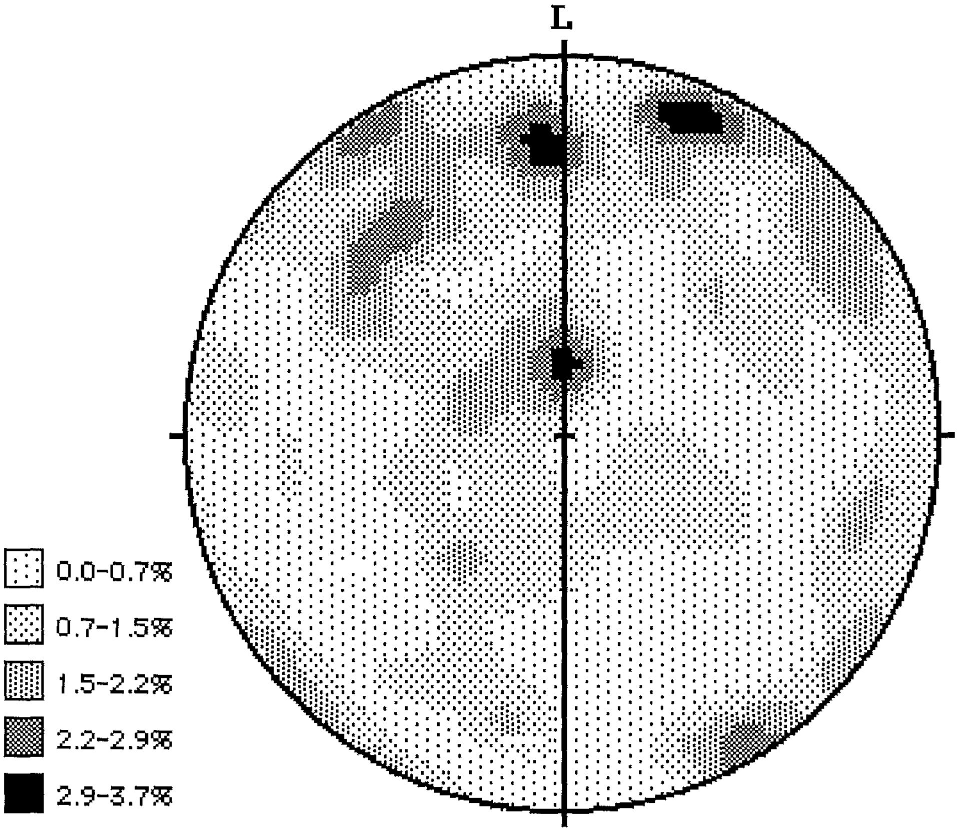


Fig39: Sample SP40 quartz c-axes. See Fig31. N=304.

Asymmetric girdles approximately perpendicular to the lineation are the normal result of basal slip along the a-axes, and it is this asymmetry which can be used to determine shear sense. Although an asymmetry is present in the Tata Beach sections, and may indicate a shear sense, it is clear that the slip system is different from the common basal <a> system.

The most likely system to produce such a pattern is prism <c> slip. This has been recognised by other workers (Lister & Dornsiepen, 1982; Blumenfeld et al, 1986; Gapais & Barbarin, 1986; Garbutt & Teyssier, 1991), but produces single point concentrations at or about the X finite strain axis (lineation). An argument for invoking prism <c> slip for the Tata Beach samples is that it is active only at high temperatures (> 650°C, Mainprice et al, 1986), and is likely to be dominant at 780°C, the temperature of intrusion for the Separation Point Batholith (Harrison & McDougall, 1980).

However, the presence of two point concentrations about the lineation, and the weak girdles linking them, are not typical of simple prism <c> slip. It is probable that the prism <c> system is dominant, but that other systems have also influenced the distribution of the quartz c-axes. Lister & Dornsiepen (1982) document an example where the girdles of the more ubiquitous basal <a> system are rotated towards the lineation, producing crossed girdles opened by more than 90°, as prism <c> slip becomes dominant. At Tata Beach, it is possible that a reverse scenario has occurred, where the point concentrations produced by prism <c> slip are rotated to produce separate concentrations and weak girdles as basal <a> slip becomes dominant due to falling temperatures. Unfortunately, even if the active slip systems can be determined with reasonable certainty, the quartz c-axis distribution still cannot be reliably used to determine the sense of shear until correlation with other microstructural evidence is found.

6.6: CONCLUSIONS

- The Separation Point Batholith varies in composition from a biotite monzogranite along the east coast to a hornblende - biotite granodiorite in the west.
- The western boundary is marked by rocks ranging in composition from syenogranites, through hybrid hornblende monzogranites and granodiorites, to diorites.
- These rocks are highly strained, displaying reduced grain sizes, crenulate grain boundaries, and elongate quartz ribbons.
- Enclaves within the batholith are fine-grained diorites or quartz diorites.
- U-Stage studies of the highly strained rocks of Tata Beach showed quartz c-axes to form two concentrations symmetrically disposed about the lineation in a plane perpendicular to the foliation.
- This quartz c-axis distribution is ambiguous, but probably represents deformation dominated by prism <c> slip, possibly overprinted by basal <a> slip.
- Neither the microstructures nor the U-Stage results gave any indication of the sense of shear.

CHAPTER 7

MAGMA GENESIS

7.1: INTRODUCTION

Recent studies have revealed an unusual geochemical signature for the Separation Point Batholith, and are particularly important to models of magma genesis (Muir et al, 1994a & 1995a). The unusual signature includes high concentrations of Sr (>1000 ppm) and Na (Na_2O / K_2O = 1.5 - 2.0) as well as high Al_2O_3 and La/Yb ratios. These features have been recognised in high-Al trondhjemite-tonalite-dacite (TTD) suites by other workers (Defant & Drummond, 1990; Drummond & Defant, 1990; Atherton & Petford, 1993) and two genetic models have been put forward. This chapter will look at these models, compare them to the signature of the Separation Point Batholith, and discuss the implications, particularly with respect to the tectonic conditions for such magma genesis.

7.2: MODELS FOR HIGH-AL TTD GENESIS

7.2.1: Melting of Young Subducted Lithosphere

Drummond & Defant (1990) investigated the geochemical characteristics of TTD suites as recorded in the literature. They recognised several features, such as high Al and Sr, depleted HREE and Y, and absent or positive Eu anomalies, which indicate that these magmas could be derived from a partial melt of metamorphosed basaltic material, leaving a garnet amphibolite to quartz eclogite residue.

They suggested that such conditions are only likely to occur where mid-ocean ridge basalt (MORB) is subducted and subjected to dehydration melting, and that only those down-going slabs that are young (<25 Ma) will be hot enough to melt in this manner. Therefore, the tectonic environment for such magma genesis is along a subduction zone, not far from the spreading centre that is the source for the MORB, with melting occurring at the corner of the mantle wedge, outboard of any main plutonic arc.

7.2.2: Melting of Newly Underplated Basaltic Crust

Atherton & Petford (1993) described the occurrence of a high-Al TTD suite inboard of the main plutonic arc of the Andes. This suite could not have formed from the down-going slab being subducted nearby because it was too old (60 Ma). Instead, they concluded that the magma was derived from basaltic material that underplated the Andean continental crust. Such basaltic underplate is formed when mafic magma rises to meet the base of the continental crust, and is trapped there. Studies of magma densities (eg Herzberg et al, 1983) show that even molten tholeiitic basalt is too dense to penetrate crustal material of dioritic or granitic composition, and instead is accreted to the base, transferring its heat energy to the continental crustal material above.

The possibility of such underplated material generating high-Al TTD magma was dismissed by Drummond and Defant (1990) because the basalt will not have reached the amphibolite-eclogite transition, and any partial melting would leave a plagioclase-rich residue. However, Atherton & Petford proposed that if the crust was thickened to around

50 km, then plagioclase would become unstable and the garnet-clinopyroxene residue required to produce a high-Al TTD magma would be stable. The tectonic environment for such magma genesis is therefore the base of thickened continental crust which has been recently underplated by mantle or slab derived basaltic material.

7.3: GENESIS OF THE SEPARATION POINT BATHOLITH

7.3.1: Subduction of a Mid-Ocean Spreading Ridge

Initial interpretations of the geochemistry of the Separation Point Batholith linked the magma genesis with the subduction of a nearby spreading ridge (Muir et al, 1994a). The presence of a spreading centre near New Zealand at the time was proposed by J. D. Bradshaw (1989) to explain the sudden change in tectonic regime that occurred in the late Cretaceous. He suggested that a ridge-trench collision led to a change from compression to extension, and ultimately resulted in the isolation of New Zealand. Muir et al (1994a) recognised this as a potential source for high-Al TTD magma, the proximity of a spreading centre ensuring a young age for any subducted MORB. This was particularly well supported by a very similar situation in the Gulf of California during the Miocene (Rogers et al, 1985; Saunders et al, 1987).

7.3.2: Melting of the Underplated Median Tectonic Zone

A later, more detailed study of the isotopic nature of the Separation Point Granite has led to a different genetic interpretation (Muir et al, 1995a). Because the isotopic characteristics are not MORB-like, and hence the granite is unlikely to be derived from a down-going slab, the source is

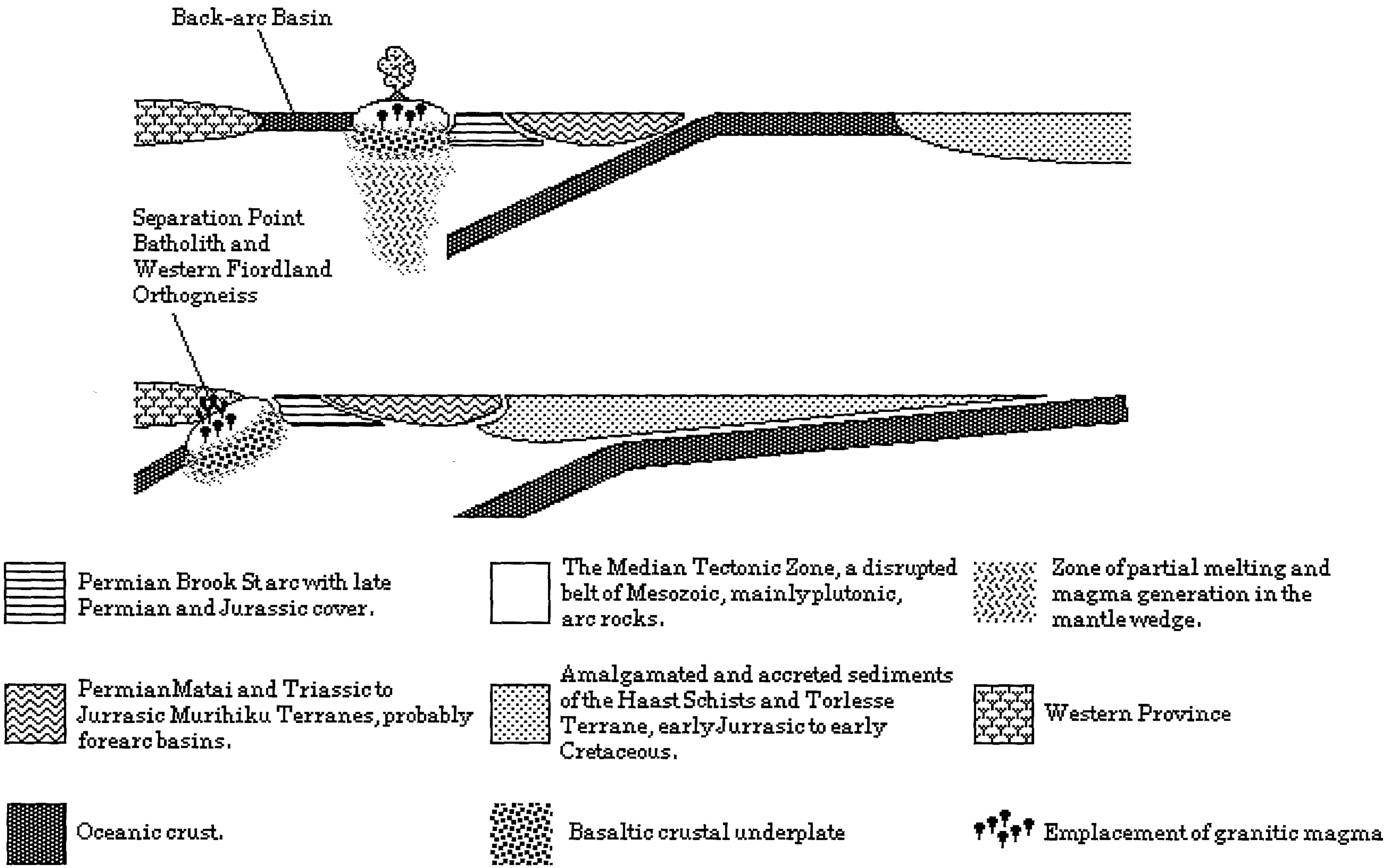


Figure 41: Schematic sections across the Pacific margin of Gondwana in the New Zealand region in the Late Jurrasic and Early Cretaceous (after Muir et al, 1995a). The top figure illustrates subduction and magma generation beneath the Median Tectonic Zone at around 140 Ma. The lower figure illustrates the following compression and crustal overthickening that leads to the generation of the Separation Point Batholith.

now interpreted to be basal arc material which melted due to collision and crustal thickening. This no longer links the genesis of the Separation Point Granite with the arrival of a spreading centre. Indeed, the preferred scenario is one of intense compression, just prior to the arrival of the spreading centre and the extension that follows.

The source of the basal arc material is basaltic underplate beneath the Median Tectonic Zone (Fig 41). This underplate was produced during the Mesozoic, as part of the subduction-related magmatism occurring inboard of the Gondwanan Pacific Margin (J. D. Bradshaw, 1993; Kimbrough et al, 1993). The arrival of large volumes of buoyant sediments to the subduction zone appears to have triggered a period of intense compression, as they refused to be subducted. This led to the subduction of a hypothetical back-arc basin that divides the Median Tectonic Zone from the Western Province, which, in turn, drags the Median Tectonic Zone under the Western Province (Fig 41). The deep burial of the Median Tectonic Zone results in the melting of its basaltic underplate and the generation of the Separation Point Magma, following the model of Atherton & Petford (1993). This series of events, as proposed by Muir et al. (1995a), is then followed shortly after by the cessation of compression and the evolution of an extensional regime (J. D. Bradshaw, 1989; Muir et al, 1994a; Waight, 1995).

7.4: CONCLUSIONS

- The geochemistry of the Separation Point Batholith is similar to that of high-Al TTD suites.

- Such suites are generated either from young subducted lithosphere or from underplate beneath overthickened continental crust.
- The lack of MORB isotopic signatures suggests that the source is basal arc material.
- Tectonic reconstructions suggest that the base of the Median Tectonic Zone was subjected to anatexis following partial subduction and overthickening as it was brought into juxtaposition with the Western Province.

CHAPTER 8

EMPLACEMENT MECHANISMS

8.1: INTRODUCTION

There are many problems associated with the genesis and emplacement of the Separation Point Batholith. For example, what emplacement mechanisms were involved and what were the tectonic conditions during emplacement? How was such a large, elongate and homogeneous batholith emplaced in such a short time? And why is the batholith oriented north / south when most contemporary structural trends are oriented north-east / south-west?

8.2: TIMING OF GENERATION AND EMPLACEMENT

The extensive yet homogeneous nature of the Separation Point Batholith has been ascribed to the rapid generation of the magma (Muir, pers. comm.), and this is supported by the low variance of crystallisation ages within the batholith, and the rapid rate at which the Median Tectonic Zone was buried. The youngest rocks in the Median Tectonic Zone are 131 Ma (Kimbrough et al, 1993), while the oldest rocks derived from them (125 Ma Western Fiordland Orthogneiss) crystallise only 6 Ma later, suggesting unusually rapid burial of such continental crustal material. However, the age difference between the Western Fiordland Orthogneiss and the Separation Point Batholith (118 Ma, Muir et al, 1994b) suggests that the magma generation was actually more prolonged, and that the homogeneous nature and narrow age range of the batholith is due to rapid, large scale emplacement, not rapid magma generation.

The late-Cretaceous period sees the development of several new structural features in the Western Province (Muir et al, 1994a). These include the Paparoa metamorphic core complex, the opening of the Pororari Group sedimentary basins, and the intrusion of lamprophyre dike swarms. All of these structures are the result of north-east / south-west extension, and the north-south orientation of the slightly older Separation Point Batholith is notable in its deviation from this trend.

Although all of these features are the result of later extension, it is possible that these trends have maintained a similar orientation to the compression which pre-dated this extension. This is particularly likely if the extension is a direct response to the overthickening of the crust during compression. This hypothesis of extension as a result of relaxation and crustal thinning was invoked by Waight (1995) to explain the generation of the Hohonu Super-suite.

8.3: EMPLACEMENT MECHANISMS

8.3.1: Passive versus Active Emplacement Mechanisms

Many mechanisms for the emplacement of granitic batholiths have been developed (eg see Brown, 1994, for a review) but most can be placed into one of two classes. Passive emplacement mechanisms, such as diapirism, ballooning and stoping, occur with minimal tectonic involvement, the granite being driven by its own buoyancy. These mechanisms are unlikely to play a major role in the emplacement of the

Separation Point Batholith, as the batholith shows extensive evidence of tectonic influence (see Chapters 5 and 6). In contrast, mechanisms such as sheet intrusions (eg McCaffrey, 1992), dyking (eg Hutton, 1992) and fault-controlled emplacement (eg Hutton et al, 1990; Grocott et al, 1994) require active tectonic involvement, and are distinguished by pervasive and consistent structures relating to the resulting regional stresses.

8.3.2: Transpressional versus Transtensional Tectonic Regimes

The orientation of structures in the Separation Point Batholith suggests that emplacement occurred under either transpressional (dextral strike-slip with east-over-west thrusting) or transtensional (sinistral strike-slip with top-to-the-east extension) conditions (Chapter 5). There are therefore two possible mechanisms for emplacement: (1) filling fractures and fault systems formed under an extensional regime, or (2) emplacement into a releasing bend of an oblique shear zone under a compressional regime.

Emplacement under an extensional regime explains best the large size and rapid emplacement of the batholith. The generation of the melt could occur under the compressional regime which subducted the Median Tectonic Zone (Muir et al, 1995a), and, with the rapid change towards extension which results from the subduction of the outboard spreading centre (J. D. Bradshaw, 1989), the magma would suddenly be able to intrude to higher levels. This scenario seems unlikely, however, as intrusion under an extensional regime usually results in magmatic structures dominating the fabric, without any evidence of the regional stresses as seen in the Separation Point Batholith. It also does not explain the north-south orientation of the batholith, or that the onset of extension is considered to have begun somewhat later than the 118 Ma age of the Separation Point Batholith (Muir et al, 1994b).

Although emplacement under a compressive regime appears improbable, at first, due to the required rapid rate of intrusion of such a large volume, the oblique, north-east angle of compression, as indicated by the lineation data, suggests that emplacement occurred under conditions which included a significant strike-slip component. Under these conditions, magma can be intruded into releasing bends along major strike-slip shear zones (Brown, 1994). Mechanisms for the emplacement of magma under transpressive regimes have been put forward by D'Lemos et al(1992). After investigating the Cadomian belt in north-west France, which exposes sections through the upper and middle crustal levels of an orogenic belt, they have developed a model by which granite can be intruded in 'megadikes' along strike-slip shear zones. The granitic magma is driven by alternating dilation and compression, aided by its own buoyancy, through middle crustal shear zones, a process described by Brown (1994) as 'strike-slip dilatancy pumping'. Final emplacement into brittle upper crust is achieved by intrusion into extensional jogs along related, overlying fault systems.

Perhaps most importantly, D'Lemos et al (1992) pointed out that the association of granitic intrusion and large scale shear zones is not merely coincidental - the generation and concentration of large volumes of magma inevitably leads to thermal softening in the rocks above. This can focus deformation into the area immediately above the zone of magma generation, and provide both the emplacement mechanism and the opportunity for intrusion.

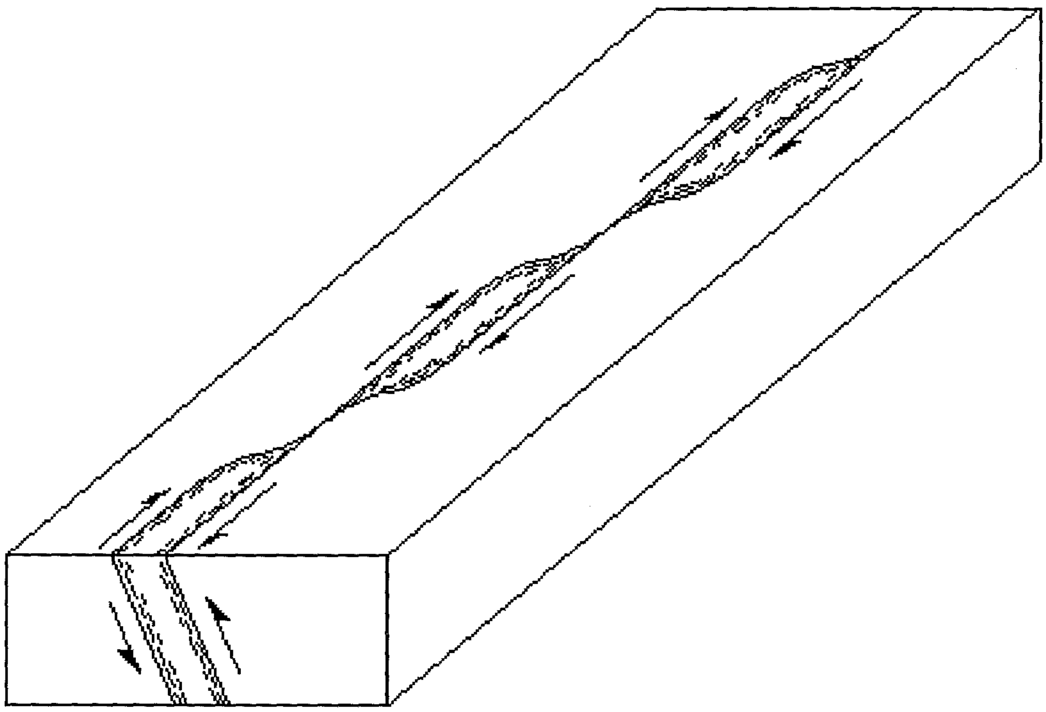


Figure 42: Development of releasing bends in a transpressive shear zone, allowing for the intrusion of large volumes of granitic magma. High-strain zones are indicated along the margins, as represented along the coast-line at Tata Beach.

The Separation Point Batholith displays several features which suggest that it was intruded under similar transpressive conditions to those described by D'Lemos et al (1992): the oblique orientation of the linear structures, relative to the planar foliation and the overall north-south trend of the batholith, supports an oblique orientation for the regional stress regime; the development of a consistent fabric throughout the batholith, irrespective of primary or secondary origin, suggests that regional stresses were a significant factor throughout intrusion and emplacement; the presence of highly deformed margins suggest that the batholith was emplaced within or along a shear zone; and the overall outcrop pattern suggests emplacement in three offset dilational jogs (cf Fig 1 with Fig 42).

8.4: CONCLUSIONS

- The extensive and homogeneous nature of the Separation Point Batholith is due to rapid emplacement of the granite magma.
- The batholith was emplaced under tectonically active conditions, as indicated by the pervasive presence of deformational structures.
- Emplacement under an extensional regime is unlikely to produce such structures. Therefore, the most probable regime is one of transpression, with dextral strike-slip and east-over-west thrusting.
- The granite was intruded into a shear zone oriented obliquely to the regional stress system (north-south).
- The oblique angle of compression enabled the granite to be emplaced along releasing bends in the transpressional shear zone.

SUMMARY

Structural features from over a wide area of the northern segment of the Separation Point Batholith were examined and recorded in order to shed light on the tectonic regime at the time of its emplacement. The most useful structures in this respect have been the lineation, foliation and jointing systems, which combine to indicate that there was a north-east / south-west movement direction along a plane dipping moderately to steeply to the east.

Examination of the coastal exposure of the western margin identified it as an area of high strain and compositional heterogeneity, ranging from relatively undeformed diorite, to granite exhibiting elongate quartz ribbons and grain-size reduction.

The internal structure of pegmatites and aplites were found to be variable and often complex, ranging from simple tabular aplites to asymmetrically zoned irregular pegmatites and combined aplite-pegmatite bodies. The internal structures relate well to current theories for pegmatite genesis. However, structural relationships between pegmatites and other features were found to be extremely variable and difficult to interpret reliably.

The common occurrence of elongate enclaves was found to be useful in indicating the direction of magmatic flow, particularly after study showed them to be magmatic in origin, suggesting that later deformational events had little impact on their orientation. Mesoscopic and microscopic investigations to determine the sense of shear for the

strain evident throughout the batholith proved to be less successful, but U-Stage studies did reveal an unusual pattern of quartz c-axis distribution in the highly strained rocks of the western margin. This pattern appears to be a result of the activation of multiple slip systems, with a prism <c> slip system being dominant.

Despite the lack of shear sense indicators, the movement direction has been inferred to be oblique transpression from the north-east. This was determined from the consistent orientation of the primary structures over the whole of the study area, and from tectonic reconstructions for the time of emplacement. The correlation of both primary magmatic structures and later deformational features suggests a strong tectonic influence throughout emplacement, reinforced by the presence of intense strain along the western margin.

The presence of a compressional regime has been inferred from both models for magma genesis, which require intense compression and crustal overthickening, and later extensional events, which appear to result from crustal relaxation and thinning in response to such overthickening. A model of emplacement for the Separation Point Batholith has therefore been developed whereby the batholith was intruded under a transpressional regime along a crustal scale shear zone, and emplaced into dilational jogs in fault systems at higher levels. The development of such a shear zone may have been assisted by thermal softening of the lower crust by magma genesis, providing the opportunity for rapid emplacement, as implied by the homogeneous nature of the batholith, and the low variance in crystallisation ages.

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